INTERPRETATION OF TOPOGRAPHIC AND GEOLOGIC MAPS

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With Special Reference to Determination of Structure

BY

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PREFACE

The field of map interpretation is singularly lacking in anything approaching an adequate textbook, largely as a result of the fact that the numerous maps considered essential increase the cost of a text almost prohibitively. The only agency suitably equipped to produce an adequately illustrated treatise on map interpretation is the Federal Government. Its one essay in this field, Professional Paper 60, "The Interpretation of Topographic Maps," has never been repeated. This book, though invaluable, contains little information on the reading of structure from contours, and still less on the interpretation of geologic maps.

Lack of a suitable text has tended to limit the number and scope of courses in map interpretation, and has in considerable measure deprived the teaching of elementary geology of one of its strongest assets, adequate map illustration. Listing illustrative maps in the general texts is admirable, but, unfortunately, the beginner without laboratory guidance sees only a small fraction of the significant features. A number of small but useful manuals on various phases of map interpretation have appeared, largely in the form of questions, but these manuals demand a skilful instructor to make them of most value.

Map interpretation lends concreteness to general and structural geology and has been termed by one of our ablest teachers an "indoor field course". It may, in part, wisely replace field studies, with economy in time and money, and has the very real advantage that more of a region or a structure can be visualized at one time on a map than in the field.

For these reasons the authors feel that there is a real place for a treatise of the type herewith presented. The material has been accumulated by the senior author through more than ten years of active teaching of map interpretation. The book was planned

several years ago to include actual maps; but after fruitless conferences with several publishers the plan was abandoned, owing to the expense involved; and it was decided to prepare a text which would refer to the maps of the United States Geological Survey, by way of illustration.

It is sincerely hoped that the work will stimulate the general interest in map interpretation, to the end that many more courses will be offered in that subject than now, and that it will help to enrich the illustrative teaching of general and structural geology.

The major plan of the work and much of the detail have resulted from the senior author's experience in teaching map interpretation. The junior author has assisted throughout in the assembling and analysis of illustrative material, and is chiefly responsible for certain minor sections of the text.

It is desired, at this point, to express the obligation of the authors to A. K. Lobeck, of the University of Wisconsin; W. A. Johnston, of the Canadian Geological Survey; W. D. Smith, of the University of Oregon; Frank Leverett, Sidney Paige, N. H. Darton, and G. R. Mansfield, of the United States Geological Survey; and R. C. Tucker, of the West Virginia Geological Survey, for information regarding the geology of certain areas studied by them. They are also indebted to Professors Josiah Bridge and G. A. Muilenburg, of the Missouri School of Mines, for many valuable suggestions; and to Professors Eliot Blackwelder, of Stanford University, and D. W. Johnson, of Columbia University, for the inspiration of unexcelled courses in map interpretation.

For the fundamental facts of geology and physiography, the authors are indebted to many of our standard texts and reference works. It is, of course, impossible to give adequate individual credit for facts drawn from so great a variety of sources.

THE AUTHORS.

ROLLA, MO.,
May, 1925.

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PART II

INTRODUCTION

The maps utilized as references in this work are, for the most part, those published by the United States Geological Survey. The topographic maps are all available for purchase at the rate of 10 cents per single copy, or 6 cents in wholesale lots, except for a few special sheets. Geological maps in the form of Folios range in price from 25 cents to $1. So far as practicable, references have been confined to maps still in print. All the maps can be consulted in the libraries of the larger colleges and universities. Many of them are also available in the offices of mining and oil companies.

Inquiries as to availability or price should be addressed to The Director, United States Geological Survey, Washington, D. C., and remittances, in the form of cash, post office money order, or draft, should be sent to him. Maps reported out of stock can sometimes be purchased through the Superintendent of Documents, Washington, D. C. Inquiries regarding Canadian maps should be addressed to The Director, Canadian Geological Survey, Ottawa, Ont.

Preceding each section is a list of maps referred to therein. These should be at hand for the study of the section. Not all the maps in such a list illustrate the topic of the section, since others are inserted by way of specific contrast. Rather long supplementary lists are added at the end of each section, so that the reader may choose from regions of special interest.

The book is divided into two somewhat distinct sections, the first dealing with the reading of topographic, the second with geologic, maps. A knowledge of general geology and plane trigonometry is assumed, and an understanding of plane surveying is desirable.

INTERPRETATION OF TOPOGRAPHIC AND GEOLOGIC MAPS

PART I

INTERPRETATION OF TOPOGRAPHIC MAPS

INTRODUCTORY STATEMENT

It is possible to learn much about the nature of the rocks and their attitude from carefully made topographic maps; and anyone contemplating geologic mapping of any type will find it worth while to study carefully all such available maps of the area, both before and during field work.

The purpose of Part I of this manual is to discuss, with illustrations chosen from actual topographic maps, the relations which may exist between structure and topography. In order, however, to gain any adequate conception of this relationship, the observer must be reasonably familiar with the common agencies that shape land forms, and with the appearance of these forms, on topographic maps, through the various stages of their development.

After a brief preliminary treatment of scales, methods of indicating relief, and interpretation of contours and contour intervals, some space will, therefore, be devoted to a discussion of the chief land forms and their history. These discussions and illustrations should prove entirely adequate for the use of the average reader of topographic maps, and for general courses in map interpretation, but cannot be expected to cover the needs of the specialist in physiography, or to fill the demand for gradu-

ate courses in that subject. To include the more specialized phases of physiographic interpretation would enlarge the book beyond suitability for its more immediate purpose, the reading of geologic structure from maps.

Finally, a word of caution must be added as to the reliability of available maps. On very small scale maps, with large contour intervals, particularly those made many years ago, much significant detail has been completely omitted, or so generalized as to be badly obscured. For this reason, structural deductions from many of the older maps are likely to be unreliable, or, in extreme cases, entirely impossible, in areas where the more modern detailed maps would yield a wealth of valuable information. Specific instances of this will be pointed out in the following discussions.

SPECIAL FEATURES OF MAPS

DIRECTION AND ORIENTATION

Maps

Charleston School sheet, Cal.

Unless otherwise specifically indicated on a map, the top is north, and the right-hand edge, consequently, east. On maps showing meridian lines, these, of course, represent true or astronomical north. In other cases, north is shown by an arrow. Ordinarily, on published maps, the indicated north is astronomical, not magnetic, the difference between the two, known as the magnetic declination, being indicated by the angle, expressed in degrees, between two diverging lines commonly shown on the lower margin of the map (Charleston School sheet, Cal.). The declination is slowly changing, and on the older maps the indicated angle may not correspond with its present variation, which can always be determined from the isogonic chart published yearly by the United States Coast and Geodetic Survey.

Orientation consists in placing the map so that its directions coincide with those in the field. A simple device for determining

direction if no compass is available is to point the hour hand of a watch at the sun, the dial being horizontal, in which position a line halfway between the hour hand and twelve o'clock is approximately south. At night, north is readily determined by the position of the polar star. In cloudy weather, orientation can be easily accomplished if such features as houses, roads, or prominent landmarks can be identified. By standing at one such known point, and making the line on the map between it and another known point coincide with the same line of sight on the ground to the same point, the map may be properly oriented.

In the field, the best results are obtained if the map is kept continuously oriented, while under observation. If one is driving south along a road, for instance, and trying to follow the map, it is best to keep the bottom of the map south, even though it is upside down to the observer. Otherwise, objects on the right side of the road show on the left of the map, and vice versa, which causes confusion in recording data. Extensive observation seems to show that fewer errors of location occur when maps are kept properly oriented.

SCALES

Maps

Charleston School, Cal.
Lehigh, Iowa
Lakin, Kan.
Ballarat, Cal.–Nev.
Sheep River, Alta.
Chu Chua Creek, B. C.

The scale of the map is the ratio of a given distance, as represented on the map, to the same distance on the surface of the earth. Scales are of three common types: the *graphic*, the *fractional*, and the *verbal*.

Graphic Scales

A graphic scale consists of a line divided into units representing miles or fractions of a mile (kilometer, etc.) to be applied directly to the map in measuring the distance. Such scales are most commonly employed on maps designed for public school and general use, because they are most easily interpreted. They have

the advantage that, in case a map is enlarged or reduced by photography, the scale is proportionately enlarged or reduced, and is still correct.

Attention should be called to the fact that commonly the zero of the scale is 1 mile (kilometer, etc.) from the end, the left-hand unit being finely subdivided (Charleston School sheet, Cal.). Errors of measurement not infrequently result from failure to realize this fact.

Fractional Scales

A fractional scale is the ratio, expressed in the form of a fraction, between a given distance as represented on the map and that distance on the earth's surface. It is commonly termed the *representative fraction*, or R. F., of the map. Since there are 63,360 inches in a mile, an inch to the mile, expressed as a fraction, would read:

$$\frac{\text{Distance represented on the map, in } \textit{inches}}{\text{Distance on the earth, in } \textit{inches}} = \frac{1}{63{,}360}.$$

Since this is an awkward figure from which to derive multiples or divisors, the scale adopted as the United States Geological Survey standard is

$1/62{,}500$ = approximately 1 inch to 1 mile (Lehigh, Iowa).
$1/125{,}000$ = approximately 1 inch to 2 miles (Lakin, Kan.).
$1/250{,}000$ = approximately 1 inch to 4 miles (Ballarat, Cal.-Nev.).
$1/500{,}000$ = approximately 1 inch to 8 miles (state geological map of Missouri).
$1/1{,}000{,}000$ = approximately 1 inch to 16 miles (millionth map of the world).

These scales fit the widely adopted "millionth" map of the world, and form a convenient series. Some of the maps issued by the Canadian Government use the above scales (Sheep River, Alta.); others employ the exact scale $1/63{,}360$ and its multiples and divisors (Chu Chua Creek, B. C.).

In the larger scales this approximate series departs more widely from the inch-to-the-mile base; that is, $1/62{,}500 - 1/63{,}360$,

which represents the discrepancy between the approximate and the exact inch-to-the-mile scales, is less noticeable than $1/31{,}250$ − $1/31{,}680$, the discrepancy between the approximate and the exact 2-inches-to-the-mile scales, the latter discrepancy being twice as large as the former. Therefore, while $1/31{,}250$ is exactly twice the scale $1/62{,}500$, it is commonly replaced by $1/31{,}680$, which is exactly 1 inch to ½ mile (Charleston School sheet, Cal.).

The ratio of the map to the area mapped is greater, that is, each feature on the map is actually larger, with a large than with a small scale. Thus, $1/62{,}500$ is twice as large as $1/125{,}000$ the former being a larger fraction with a smaller denominator.

Although in the United States the unit 1 inch is commonly used in speaking of maps, it is to be remembered that the fraction is a ratio equally true with any unit of measure so long as both numerator and denominator are of the same terms. This fact makes the fractional scale independent of language barriers, one of its most important features.

Verbal Scales

Verbally, a scale may be expressed as "an inch to the mile", "an inch to 2 miles", etc. Commonly, and more correctly, the distance on the map is mentioned first, but not infrequently the terms are reversed, so that we often hear "a mile to the inch", and, as it would be absurd to interpret this as a mile on the map to an inch on the earth's surface, "inch to the mile" and "mile to the inch" are quite commonly used interchangeably, and mean the same thing.

When, however, one hears "2 inches to the mile" and "2 miles to the inch", both of which are in common usage, at least locally, the matter is likely to be more confusing, as will be readily seen from the following:

$$\text{2 miles to the inch} = \text{1 inch to 2 miles} = \frac{1}{2 \times 63{,}360}.$$

$$\text{2 inches to the mile} = \text{1 inch to } \tfrac{1}{2} \text{ mile} = \frac{1}{\frac{1}{2} \times 63{,}360}.$$

The second scale is thus seen to be four times as large as the first. This has been found to cause considerable confusion among elementary students of maps.

METHODS OF REPRESENTING TOPOGRAPHY

There are at least three common methods of showing relief on maps: by *shading*, by *hachures*, and by *contours*.

Shading

Relief maps designed for use in public schools commonly employ various shades to indicate areas of different elevation. This device is usually employed on small-scale maps covering such large areas as states, countries, or whole continents. As commonly applied, it gives a graphic but much generalized idea of relief.

Hachures

Hachures are a type of shading in which lines are used, usually running in the direction of slope, and therefore normal to contours (Fig. 1). The more closely the lines are spaced the steeper the slope. Hachures are sometimes combined with contours to increase the vividness of impression, but more often are used alone, as on many of the French and Swiss maps. Hachured maps are less exact than those in which the relief is shown by contours, and are seldom used in this country for engineering or geological purposes.

Contours

Commonly in the United States, relief maps for the use of geologists or engineers are printed with contours, and geological maps are commonly overprinted on such a topographic base. Since, almost without exception, the maps used in this volume show relief by contours, the matter of contouring will be given a somewhat extended discussion in the following section.

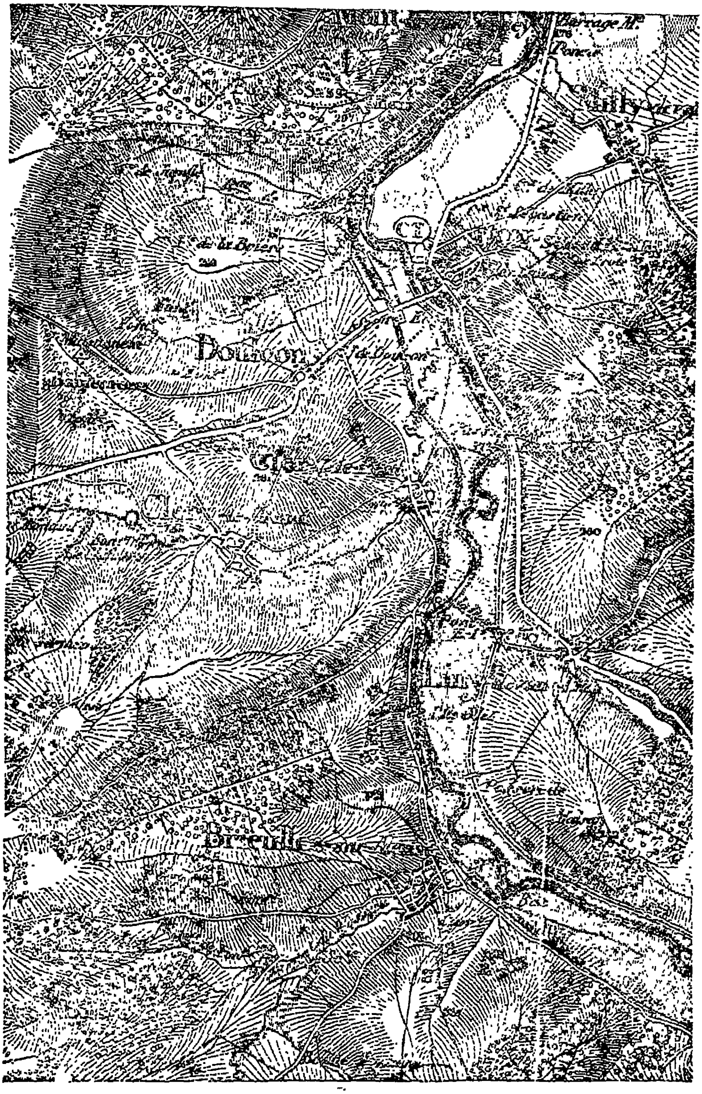


FIG. 1.—Hachures as a method of showing relief. Reproduction of part of Verdun sheet, France.

CONTOURS AND THEIR SIGNIFICANCE

Contour Lines

Maps

Yosemite Valley, Cal.

A *contour line* is a line drawn on a map (ordinarily in brown) through all points of equal elevation. Every contour, therefore, if viewed broadly enough, is a closed curve, or a group of closed curves. Commonly, however, the entire curve does not show on the area of a single map, in which case it should always be drawn to the edge of the sheet—never left "hanging". Contours are merged into one another, or superimposed upon one another, only on vertical or nearly vertical cliffs (Yosemite Valley map, Cal.) and may intersect only in the very rare instance of an overhanging cliff, the "overhang" of which is far enough to be measurable on the scale of the given map. This will happen only on very large scale detailed maps, and the writers know of no single instance on the regular quadrangle sheets of the United States Geological Survey.

Ordinarily, every fourth or fifth contour is accentuated, and numbered (in brown) to facilitate reading the map.

Contour Intervals

Maps

Charleston School, Cal.
Mt. Whitney, Cal.
Apishapa, Colo.
Pueblo, Colo.
Monmouth, Ill.
Lehigh, Iowa.
Lakin, Kan.
Piedmont, Md.-W. Va.
Beaverton, Ont.
Deadwood, S. D., 1894 and 1901 eds.
Hermosa, S. D., 1894 and 1901 eds.
Aldine, Tex.
Clintonville, W. Va.
Greenland Gap, W. Va.

A *contour interval* is the difference in elevation of two successive contour lines. It has nothing whatever to do with the *distance* between contours, which is controlled by the steepness of the slope. Common intervals in use by the Survey are 5, 10, 20, 50,

and 100 feet. In rare cases 1-foot contours have been used (Aldine, Tex.), and on a few maps the interval is 25 feet (Apishapa, Colo.). On some of the earlier maps, 200- and 250-foot intervals have been employed (many of the Arizona and Utah sheets), and maps of an entire state, or of the United States, have been published with 500- or 1,000-foot intervals.

The interval is determined by the scale of the map, by the relief of the area, and, to some extent within the limits imposed by these factors, by the degree of refinement required for the purposes to which the map is expected to be put. With the inch scale ($1/_{62,500}$), 10 (Lehigh, Iowa), 20 (Monmouth, Ill.), and 50 feet (Clintonville, W. Va.) are most common, depending on relief; with the half-inch scale ($1/_{125,000}$), 20 (Lakin, Kan.), 50 (Pueblo, Colo.), and 100 feet (Mt. Whitney, Cal.); with the 2-inch scale ($1/_{31,680}$), 5 feet (Charleston School, Cal.) is commonly used.

The larger the scale, and the smaller the contour interval, the more detail can be shown, and the more accurately should the map portray the actual relief. This is well shown by the Greenland Gap (W. Va.) and Piedmont (Md.-W. Va.) quadrangles. The former, on the inch scale, with a 50-foot interval, is a resurvey of the southeast one-fourth of the latter, which is on the half-inch scale with a 100-foot interval. The larger scale, the smaller interval, and the better grade of topographic sketching being done in more recent years, are all important factors in the contrast between the Greenland Gap and the Piedmont sheets. The better quality of sketching is also well shown by the 1894 and 1901 editions of the Deadwood and Hermosa (S. D.) sheets, both of which employ the same scale and interval. The later edition shows greatly increased detail.

No contours are ever placed on a map except those that are a multiple of the contour interval, unless specifically so stated in the legend, or unless definitely numbered on the map, and even then the use of such contours is rare. For example, with a 20-foot interval there will ordinarily be no 10-foot, 30-foot, or other contour not a multiple of 20.

On some maps, "intermediate contours", halfway between the regular ones, are drawn in faint dotted lines where detail is to be shown that would not "catch" a regular contour (Beaverton sheet, Ont.).

On a few maps, in which very rugged areas contrast with very flat ones, two intervals may be employed on the same map, since an interval that would show the relief on the plains area would crowd the map too closely in the hilly section; whereas an interval suited to the mountains would show no detail in the flat parts of the map. In such cases, however, both intervals are shown at the bottom of the map, usually with a statement of the elevation at which the change occurs. Maps with two intervals are commonly misleading, as they tend to obliterate the contrast between plains and hilly areas. This is particularly well brought out on the Charleston School (Cal.) quadrangle, in which the upland appears to break off suddenly into a very steep escarpment on the 400-foot contour, because of the change from a 25-foot interval above that elevation to one of 5 feet below. If the interval were the same throughout, no such impression of an escarpment would be given.

Depression Contours

Maps

Ballarat, Cal.-Nev. Standingstone, Tenn.

Depressions without surface outlet are indicated by closed contours on the inside of which are usually drawn hachures (Fig. 3). If such depressions have valleys cut into their sides, as in some of those on the Standingstone (Tenn.) sheet, the valleys become part of the depression. In very large undrained intermontane basins, such as Death Valley or Saline Valley (Ballarat sheet, Cal.-Nev.), the contours may be numbered in descending order to indicate the depression, instead of using hachures. A discussion of the various types of depressions is presented on pages 21–26.

Contours and Land Form

The significance of a contour line can be best visualized by gradually immersing a small model of a well-dissected region in a tank of water. If the lowering be done by successive units of ¼ inch, and the shore line traced on the model at each step, it will

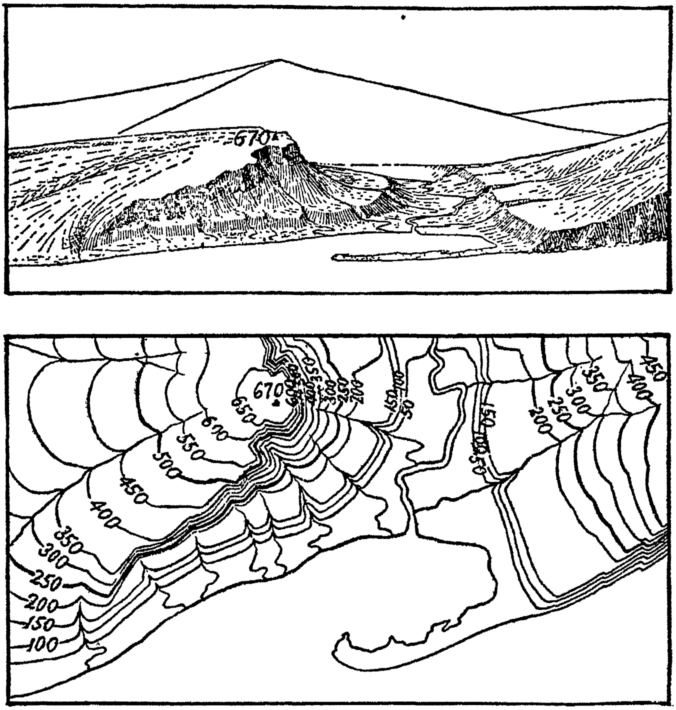


FIG. 2.—Ideal sketch and corresponding contour map. (*After U. S. Geol Survey.*)

be found on completing the work that there is a series of lines, separated by vertical intervals of ¼ inch, which bend upward toward valley heads and outward around spurs. It will be possible to cross a valley on a single contour, that is, at a constant level, only by swinging far up toward the valley head.

If these lines on the model be now projected downward or upward onto a flat surface, such as a large sheet of paper, a *contour map* of the model will be the result. It will at once be seen that the contours are closer together on steep slopes and more widely spaced on gentle slopes. Isolated hills will be shown by small, closed curves. These relations are well brought out in Fig. 2.

Numbering of Contours

Maps

Flagstaff, Ariz. Mt. Lyell, Cal.
Lakin, Kan.

Difficulties commonly arise in interpreting closed elevation and depression contours on which numbers have not been printed. These are best made clear by the use of a sketch (Fig. 3) illustrating cases which can be duplicated on actual topographic sheets. For similar examples see the Flagstaff (Ariz.) and Mt. Lyell (Cal.) sheets, representing volcanic cones with craters, and the Lakin (Kan.) sheet, showing sand dunes and accompanying depressions.

In the sketch (Fig. 3) the contours are lettered for convenience. The student should first try numbering the contours for himself, checking himself afterward by the discussion.

It is obvious that *A* is the 20-foot and *B* the 40-foot contour. Since *C* and *I* mark isolated hills next above the 40, they are each 60.

If contour *I* is 60 feet, the area inside of it, but not inside *J* and *M*, is above 60 and below 80 feet. From an area above 60 but below 80 feet one, therefore, goes up a hill to *M*, numbered 80, and down into a depression to *J*, numbered 60 feet. If *M* is an elevation contour numbered 80, the area within it, but not within *O* or *N*, is above 80 and below 100 feet. From an elevation above 80 but below 100 feet, one goes up a hill to *N* at 100 feet, and down into a depression to *O* at 80 feet.

If *J* is a depression contour numbered 60 feet (as already shown), then the area within it, but not inside *K* or *L*,

is below 60 but above 40 feet. From an area below 60 but above 40 feet, one goes down into a depression to K, which must be the 40-foot contour, and up a hill to L, which must be the 60-foot line.

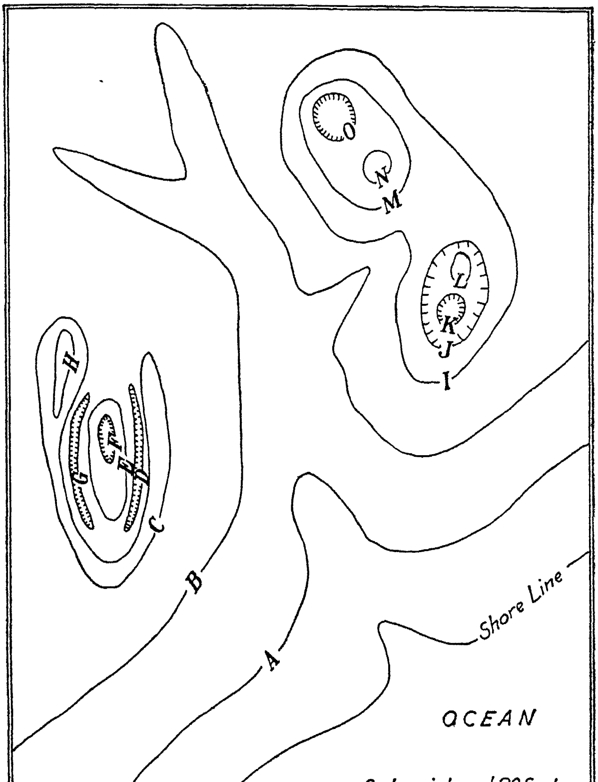


FIG. 3.—Exercise in numbering contours.

Also E is a type frequently misinterpreted. It must be noted that E is not above C. Although within the crescent made by C, E is an independent hill next above B, as may be seen by imagining C to be stretched out into a long, narrow ridge, when E will be understood to be a separate hill, contour E having the same elevation as C, that is, 60 feet.

Contours *D* and *G*, which are hachured, represent depressions in an area, the general level of which is above *B*, 40 feet, but below *C*, 60 feet If one is at an elevation between 40 and 60 feet, and goes down into a depression, the first contour crossed will be 40 feet; consequently, that must be the elevation number for contours *D* and *G*.

The elevation contour *E* has already been shown to be the 60-foot line; the area within it, but not within *F*, therefore, is above 60 but below 80 feet, so that the first contour crossed in going into the depression *F* would necessarily be the 60-foot line. Since *H* is an elevation contour within *C*, 60 feet, it must be the 80-foot line.

Limits of Exactness in Reading Contours

Maps

Charleston School, Cal.

Ordinary topographic maps make no claim to mathematical precision. Critical points, such as the tops of hills, the bottoms of valleys, the base and the crest of cliffs, and points at which slope changes notably, are usually determined rather closely, but no effort is usually made to have instrumental "shots" coincide with contours, these being interpolated by the topographer. An experienced sketcher will map an area with a few well-selected actual elevations, and produce a more accurate map than will a beginner with three or four times as close control. The topographers responsible for the work are commonly indicated in a small rectangle on the lower margin of the map (Charleston School sheet, Cal.).

The chief effort is centered on producing "expressive" as contrasted with "wooden" topography, that is, on showing all features of the land forms even though elevations are only approximate. Errors of from a quarter to half a contour interval, in placing contours, are permissible, and much greater ones are fairly common, and the user of topographic maps must under-

stand this fact. A high degree of precision would render the cost of topographic sketching prohibitive for most purposes. Ordinarily, the sketching is most accurate in open country and along main roads, while in areas of thick woods many small gullies are often overlooked. Sometimes on the older maps the head of one valley is even connected with the lower course of another, a situation very confusing to the geologist who uses the minor drainage to locate himself in the field.

The elevation of any point above sea level, were the contours exact, could be told with precision on a contour line, and within an interval between contours. On slopes that are fairly regular,

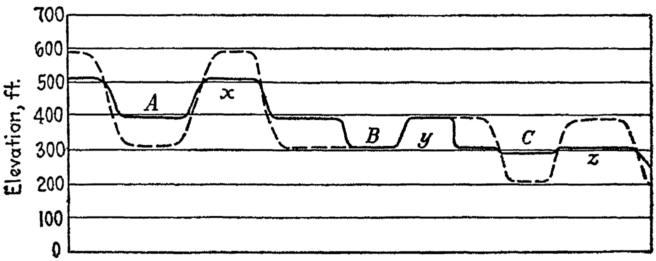


FIG. 4.—Illustrating the limits of exactness in reading contours.

interpolations can be made with some confidence, so that a point halfway between the 20- and 40-foot contours will be about 30 feet. In rugged country, where slopes change rapidly, such interpolations are less dependable.

A common misunderstanding arises, in attempting to determine the depth of a depression below its rim or the height of a hill above its base, because the depth or the height is not referred to a definite plane, such as sea level, but to an elevation which is itself subject to misinterpretation within the limits of a contour interval; so that with a variable of an interval at the top, and another at the base, the limit of error is twice the contour interval. This will, perhaps, be made clearer by a study of Fig. 4. In this figure, which represents a profile section, the numbered horizontal lines represent contours with an interval of

100 feet, and the irregular line represents the topographic profile across a region with three depressions A, B, and C.

The depression at A is drawn with both solid and dotted lines, both profiles showing two contours (on a map marked with hachures) within its walls. The solid profile shows a depression a trifle over 100 feet deep; the dotted profile, with exactly the same number of contours, indicates a hole nearly 300 feet deep. Similarly, the depression at C shows only one contour within it, and can be interpreted as only a few feet deep (solid line), or as nearly 200 feet deep (dotted line).

Depression B is so placed that, even though it is nearly an interval deep, it does not "catch a contour". This should be contrasted with the one at C (solid line), which, though only a few feet in depth, is so placed that it "catches a contour".

From the above cases, it should be clear that, in general, the depth of a depression cannot be positively determined on a topographic map. Since there is a variable of an interval at the top and an interval at the base, the limit of accuracy is twice the contour interval. The maximum possible depth is always a number of intervals greater by one than the number of depression contours showing, and the minimum is always a number of intervals less by one than the number of depression contours. To be specific, with three contours showing, the range is between two and four intervals; with four contours, between three and five intervals.

A moment's reflection will show that in reading the height of an isolated hill, not above sea level but above its base, the same uncertainty exists, and the principles laid down for depressions in the preceding paragraphs also hold for such isolated elevations. Thus, in Fig. 4, x may be considered to be a hill, showing two contours, the height being somewhere between a maximum (dotted line) of three intervals and a minimum (solid line) of one interval. Also y illustrates how a hill can be nearly an interval in height and not "catch a contour", and z shows how a hill only a few feet high may "catch a contour" even with a 100-foot interval.

DRAWING TOPOGRAPHIC PROFILES

The geologist most commonly draws topographic profiles for the purpose of inserting structure. Such structure sections will be discussed in the part devoted to geologic maps (pp. 322–324). It not infrequently happens, however, that the geologist draws a topographic profile for the purpose of showing only topographic relations or contrasts.

One of the common defects is undue exaggeration of the vertical scale. Of course, railroad and road profiles used extensively by civil engineers must often have a large vertical scale, since they must show small differences of elevation with a magnitude that permits scaling them off the drawing. It is also true that a certain amount of exaggeration is permissible, in profiles drawn for geologic or physiographic purposes, in order to show minute detail. On the other hand, much exaggeration tends to give a false idea of the relative depth and width of valleys, or height and width of mountains. Also, where structure is to be inserted in the profile, exaggeration of the vertical scale greatly distorts the apparent position of the beds (p. 322). For this reason, students of map interpretation should draw many profiles to natural scale, that is, with the vertical and horizontal scales the same.

Since this usually gives much trouble to beginners, a single illustration of procedure is given. With an inch-to-the-mile scale, 1 inch equals 5,280 feet, or $\frac{1}{100}$ inch equals essentially 50 feet, both vertically and horizontally. A pair of dividers is useful to locate the desired points along the base line of the section. If the scale on the map is to be increased two, three, or four times, for instance, the distances can be easily "stepped off" with ordinary dividers, or proportional dividers may be used. If the map is on an inch-to-the-mile scale, and the profile is natural scale but enlarged twice, 1 inch will, of course, represent 2,640 feet, and $\frac{1}{100}$ inch about 26 feet. All other scales are worked out in the same way.

The number of points to be chosen in making a profile will depend largely on the skill of the worker. Ordinarily, tops of hills, bottoms of valleys, and all points at which sharp changes in

slope occur should be plotted. It is almost never worth while to plot every contour.

The plotted points are connected by a line which represents the land surface. Here skill is required to avoid "wooden" topography. Only rarely do straight lines and sharp angles enter into such profiles, and the better the actual conditions on the ground are visualized the more nearly will the profile approach those curves really characteristic of topographic slopes.

Commonly, the base line for a profile should be sea level, in order to show the relation of the area and its relief to base level, but in some cases the vertical scale is such as to render this impracticable, and an arbitrary base is chosen, such, for example, as 2,000 feet above sea level. Local relief is shown just as accurately, but the whole relation to permanent base level is lost sight of.

DESCRIBING LOCATIONS ON A MAP

Maps

Lakin, Kan. Crystal City, Mo.-Ill.
Cadiz, Ohio.

Most of the quadrangles of the United States Geological Survey are divided by the parallels and meridians into nine smaller rectangles, and these serve as a convenient means of locating points. Various schemes of numbering these rectangles have been used by different teachers in the classroom. It is, however, but little more trouble to name the rectangle than to number it, and then there can be no confusion. In these pages, the rectangles will be known as follows (given in the abbreviated form):

Northeast rectangle....................	= NE. rect.
North central rectangle..................	= N. cent. rect.
Northwest rectangle....................	= NW. rect.
East central rectangle..................	= E. cent. rect.
Central rectangle......................	= Cent. rect.
West central rectangle..................	= W. cent. rect.
Southeast rectangle....................	= SE. rect.
South central rectangle..................	= S. cent. rect.
Southwest rectangle....................	= SW. rect.

In areas which have been sectionized, the standard land divisions constitute the best way to give locations (Fig. 5). Ranges are numbered at the north and south margins of the map, townships on the east and west margins. Township 2 North, Range 4 West, for example (commonly expressed T. 2 N.,

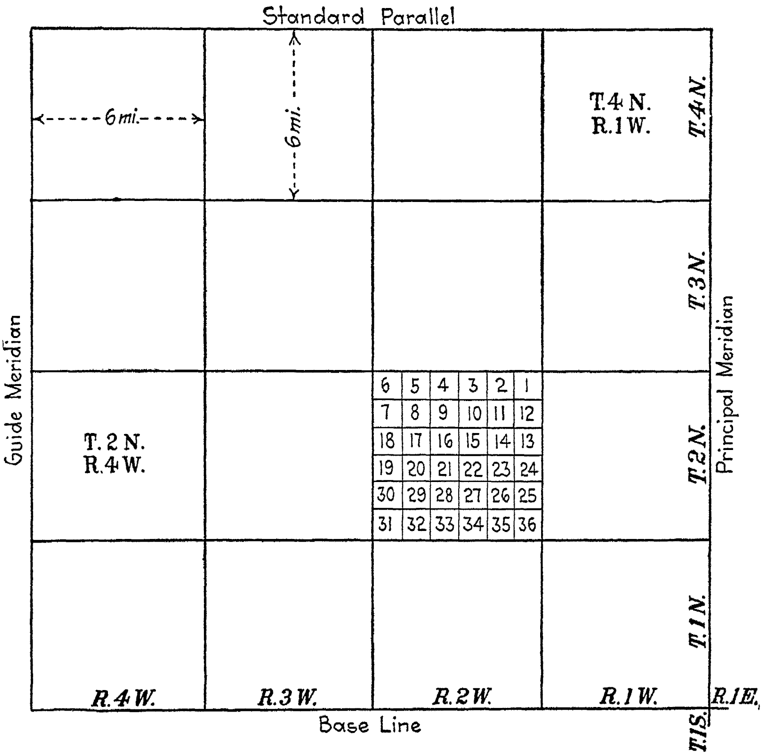


FIG. 5.—The standard land survey.

R. 4 W.), is a body of land 6 miles each way, divided into thirty-six sections numbered as in Fig. 5. Ordinarily, on a map the letters and figures used in marking townships and ranges are placed opposite the center line, the units extending 3 miles on each side, the 6-mile square being bounded by slightly heavier

lines. Beginners frequently find trouble in counting out the section, when the border of the map splits the township or range, so that only part of the sections are shown, for instance, Lakin (Kan.) sheet, T. 29 S., R. 34 W. The sections may or may not be numbered on the map. Confusion may sometimes arise on maps lying in two states using different base lines or prime meridians (Crystal City sheet, Mo.-Ill.), or in a state using more than one prime meridian or base, as is the case in Utah. Many of the eastern and southern states are not sectionized, Texas has several local systems, and in portions of Ohio sections are numbered differently from the above scheme (Cadiz sheet,) but the system just outlined is the common one in the north central and western states.

CONVENTIONAL SYMBOLS (LEGEND)

The legend of a map consists of a list of the conventional symbols used on the map, together with their explanation. Those used on the United States Geological Survey's topographic maps are printed in full on the back of each map, together with a brief explanation of the nature of scales, contours, and the basis used in mapping the United States. This descriptive matter should be studied carefully by anyone desiring to become familiar with the use of contour maps. For this purpose, one of the newer maps should be utilized, as a few of the symbols have been changed, and a few added, since the earlier maps were made.

LAND FORMS, THEIR DEVELOPMENT AND RECOGNITION

The chief agents active in shaping land forms are ground water, the wind, glaciers, waves, volcanoes, disastrophism, and running water.

Of these, running water is responsible for a much larger proportion of the familiar topographic forms than any other agent, and it is chiefly in those forms carved by running water that one finds the clue to structural interpretation.

In these pages, therefore, consideration of land forms produced by running water—which in the more familiar texts on general geology finds a place after the work of wind and ground water, and before glaciers and waves—will be deferred to the final section on "Land Forms", immediately preceding the section on "Relations of Land Forms to Structure", to which it is closely related.

TOPOGRAPHY RESULTING FROM THE WORK OF GROUND WATER

Maps

Frank, Alta.	Lansing, Mich.
Flagstaff, Ariz.	Battle Lake, Minn.
Ballarat, Cal.- Nev.	Pingree, N. D.
Malaga, Cal.	Portland, Ore.-Wash.
San Luis Ranch, Cal.	Wind Gap, Pa.
Williston, Fla.	Kingston, Tenn.
Lakin, Kan.	Standingstone, Tenn.
Meade, Kan.	Bristol, Va.-Tenn.
Bowling Green, Ky.	Quincy, Wash.
Lockport, Ky.	Clintonville, W. Va.
Bay City, Mich.	White Sulphur Springs, W. Va.

Although the work of ground water is a very vital phase of geology, it plays a relatively subordinate part in shaping topography, except in a few regions; its one important contribution to the production of surface features being the development of *sink holes.* The Standingstone (Tenn.), Bristol (Va.-Tenn.), Bowling Green (Ky.), Williston (Fla.), and Clintonville and White Sulphur Springs (W. Va.) sheets all show excellent examples of such sinks.

Depressions may originate in several other ways. They occur among sand dunes as a result of the scouring of wind or the unequal deposition of sand (Lakin sheet, Kan., p. 28); they are common in glaciated areas as a result of the melting of buried blocks of ice, or of the unequal deposition of drift (Lansing sheet, Mich., p. 34); on very recently emerged coastal plains, original depressions of unequal deposition on the ocean bottom may still persist, and pothole action on streams may produce

them, though the latter type is usually not large enough to be represented by contours on topographic maps. Exceptionally, such depressions, resulting from abandoned waterfalls, are clearly to be seen, as "The Potholes", on the Quincy (Wash.) sheet, and elsewhere on the Columbia Plateau.

Depressions may also result from various phases of volcanic activity, such as the uneven original surface of lava flows or ash deposits, from the damming of valleys by lava, or from craters. Of these types, the latter are the only ones known to show in typical form such that they can be identified on topographic sheets (Flagstaff, Ariz., p. 61).

Depressions from unequal alluviation (p. 76), are very common on flood plains, particularly in the form of partly silted channels of old oxbows (San Luis Ranch sheet, Cal.), and may usually be recognized by their form and relation to the present stream. Long, narrow depressions may also occur between beach ridges (p. 46) on a prograding shore line (Bay City sheet, Mich.), and may closely resemble in shape some of those resulting from partly silted oxbows. Depressions are also common in landslide topography, but are usually not large or deep enough to be shown on ordinary contour maps. A particularly good example, however, is shown on the Frank (Alta.) sheet. Depressions may also result from earthquake subsidence, but no good maps are known which show this type by means of contours.

Artificial depressions are also common. Those resulting from mine subsidence closely resemble sink holes, but contour maps of such do not appear to be available. Open-pit mines or quarries are also a common type (Wind Gap sheet, Pa.), as are also those caused by railroad or road fills (Portland sheet, Ore.-Wash.).

Intermontane basins of large proportions, resulting primarily from down-warping or down-faulting of considerable areas (p. 67), must also be classed among the various types of depressions, though not ordinarily shown by hachured contours (Ballarat sheet, Cal.-Nev.).

It must be obvious that many isolated depressions occur which cannot, from the map alone, be referred to their proper origin.

and in a few cases there may even be some doubt attaching to the origin of whole groups of depressions. But there are certain criteria which can be used to good advantage, in discriminating between these types in map study.

At Sinking Cane, and also at Morrison Cove, in the south half of the central rectangle of the Standingstone (Tenn.) sheet several permanent streams of considerable size flow into the depressions and disappear. A similar situation is to be noted on the Bristol (Va.-Tenn.) and Clintonville (W. Va.) sheets. There is no surface outlet, and, since the inflow is greater than can plausibly be accounted for on the basis of seepage, or of evaporation in a region obviously humid, these disappearing streams constitute evidence that the depressions are sinks, with underground outlets.

Great numbers of depressions will usually indicate some one of the three more common types—those of wind, glacial, or solution origin—though alluviation types are sometimes numerous. The entire absence among such numerous depressions of large numbers of small hills, such as mark dune and moraine topography, is also indicative of sink holes.

The depth of depressions is sometimes significant; those greater than 100 feet can usually be referred with considerable confidence either to sink-hole origin, or to volcanic craters, the latter ordinarily being easily distinguished because of their position within a definite cone. Wind-scoured depressions of that depth are rare indeed, except possibly in truly desert areas, in which other evidences of aridity would be present. Kettle holes in moraine topography rarely attain such depths, and are commonly associated with lakes; original depressions on coastal plains are probably rarely more than a few feet deep, and are always associated with a rather youthful stage of the erosion cycle, since they soon disappear, with the development of a normal drainage system. All depressions of alluviation, landslide, or earthquake origin are usually shallow, and deep artificial depressions are rare and usually isolated. Intermontane basins of great depth are also usually of large area, and quite commonly of considerable aridity.

On the Bristol (Va.-Tenn.) quadrangle, the depressions show a marked tendency to alignment, as a result of the fact that the rocks are folded, so that the limestones outcrop in long, narrow belts. Such an alignment of depressions is rarely found except in folded regions, and its occurrence is usually indicative of the sink-hole origin of the depressions. Shallow depressions, however, may be aligned along old channels, as on the Malaga, (Cal.), Pingree (N. D.), or Battle Lake (Minn.) sheets.

It is entirely possible that, in a dune area, a moraine area, or a newly emerged coastal plain, solution of underlying soluble rock may produce sinks among other types of depressions; dunes may occur in areas of glaciation, in close proximity to moraines; or the characteristic features of any type of depression may be so poorly developed that it is not possible, from the map alone, to discriminate between the types. But in many cases such discrimination is easy, from the topographic contour alone.

Since limestone is the most widely distributed soluble rock, the common inference is that sinks indicate limestone areas; but they may develop in areas where either gypsum or salt beds occur beneath the surface. So far as known, sinks resulting from the solution of salt or gypsum beds do not occur east of the Mississippi River, in the United States, but are shown on the Meade (Kan.) sheet, where they are associated with obvious dune topography, so that it is impossible to say what proportion of the depressions are related to the dunes, and what are sinks. Several of the depressions are occupied by temporary lakes, into which intermittent streams empty. The depression contours are not hachured, and can be recognized only by the numbers, or by the enclosed lakes.

An interesting deduction on the Lockport (Ky.) sheet is that, since the sink holes all occur on the lower ground along the river, the hills are probably capped with an insoluble rock, such as shale or sandstone, and the deeper valleys have cut into and partly uncovered an underlying limestone.

The Kingston (Tenn.) sheet shows a large sink, Grassy Cove (W. cent. rect.), which, at least on the older maps, is represented

not by hachured lines but by ordinary contours, with the depth at the lowest point shown in a brown figure. This sink is particularly interesting, in that it occupies a position within an anticline, the central part of which is eroded deeply enough to expose a lower and older limestone, surrounded by an inward-facing escarpment (p. 166) of more resistant rock.

The depth of sink holes varies from a few feet to more than 200 feet (Sinking Cane, Standingstone sheet, Tenn.). The rim of Sinking Cane is above 1,300 but below 1,400 feet, while its lowest point is below 1,100 but above 1,000 feet. Assuming that the rim is just above 1,300 and the base just below 1,100, the depth may not be much more than 200 feet. On the other hand, if the rim were almost up to 1,400 and the base almost low enough to "catch" the 1,000-foot line, its depth might be as great as nearly 400 feet.

On the other hand, the small depression just south of Peekville (SW. rect.), the depression contour for which is not numbered, may be very shallow. Since it lies on a plain between the 1,000 and 1,100-foot contours, one first crosses the 1,000-foot line when descending into the sink, hence that is the elevation of its depression contour. If the rim, which lies between 1,000 and 1,100 feet, is almost 1,100, and its base, which lies below 1,000 but above 900, is nearly as low as 900 feet, it might reach almost 200 feet in depth. On the other hand, if its rim were but a little above 1,000 feet, and its base but little below that line, it might be only a few feet deep, but be so placed as to "catch a contour".

On the Bristol (Va.-Tenn.) sheet are numerous examples of sink holes so situated that they do not happen to "catch a contour". They are indicated by little blue dots into which streams are seen to flow. All that can be said of their depth is that they are less than a contour interval (100 feet). They may actually be deeper than other sinks that "catch a contour" (see pp. 15–16 and Fig. 4).

It is of interest to note that in limestone regions of extensive caves there are many cases of the diversion (capture) of surface streams into underground channels (*subterranean stream piracy*).

Several such cases have been described in Missouri,[1] one of which was mapped in detail with a 5-foot contour interval.[2] Several cases of such subterranean diversion are to be noted on the Clintonville and White Sulphur Springs quadrangles of West Virginia (p. 110).

The limestone regions of Tennessee, Kentucky, West Virginia, Missouri, and Florida are especially famous for the abundance and size of their sinks. Solution depressions are much less commonly seen in the glaciated regions, probably because obscured by glacial drift. In general, the region of the Great Plains and Cordilleran highlands, while showing occasional sink areas, is less suited to their formation, because of the relatively smaller proportion of limestone or other soluble strata in their make-up and the less humid climatic conditions.

Additional maps illustrating sink holes

Tsala Apopka, Fla.	Roan Mountain, Tenn.-N. C.
Renault, Ill.-Mo.	Eagle Rock, Va.
Bloomington, Ind.	Natural Bridge special, Va.
Mammoth Cave, Ky.	Wise, Va.
Princeton, Ky.	Alderson, W. Va.

TOPOGRAPHY RESULTING FROM WIND WORK, LARAMIE, WYO.

Maps

Holtville, Cal.	Browns Creek, Neb.
Rehoboth, Del.	Chappel, Neb.
Great Bend, Kan.	Sandy Hook, N. J.
Lakin, Kan.	Bellaire, Tex.
Durand, Mich.	Moses Lake, Wash.

Laramie, Wyo.

Although the wind is a powerful erosive agent in arid regions where there is no protective cover of vegetation, many of the forms most characteristic of wind sculpturing are so small as not to be shown on the ordinary topographic map. Furthermore, thus far it has not been practicable to separate in any very

[1] DAKE, C. L., and BRIDGE, JOSIAH, Subterranean stream piracy; Univ. of Mo., Sch. of Mines and Met., *Tech. Ser. Bull.* vol. 7, no. 1, 1924.

[2] Of this a model was prepared, which is being placed on the market by Ward's Natural Science Establishment.

satisfactory manner the part played by wind from that played by running water, in the producton of the larger topographic features of our arid regions. The large depressions on the Laramie (Wyo.) sheet have been ascribed to wind origin. The evidence from the topographic map alone, however, is not convincing.

On the other hand, wind deposits are quite distinctive. The finer wind deposits, known as *loess*, and the coarser material in the form of *dunes*, are widely distributed. The topography of loessial areas is carved largely by running water, but dune areas consist of a strikingly distinctive topography fashioned directly under wind control.

The Lakin and Great Bend (Kan.) sheets, and the Browns Creek and Chappel (Neb.) sheets show large areas of typical dune topography. These areas are characterized particularly by the very great number of small isolated hills, of about the same size and height, among which are numerous depressions, in part scooped out by the wind, in part the results of unequal deposition of sand.

In appearance, dune areas more nearly resemble moraines than any other type of topography. As a rule, the abundant lakes and swamps of moraine areas are missing among dunes, though intermittent lakes may be common. Among dunes, also, the hills are likely to be smaller, more numerous, and less connected into definite ridges and chains than in glacial topography, though dunes sometimes form into definite ridges. The student will do well to contrast the dune area of the Lakin (Kan.) sheet with the moraine in the south part of the Durand (Mich.) quadrangle, to gain a clearer idea of this contrast. Occasionally, however, an area of sand dunes resembles a morainal ridge, as in the Sand Hills (Holtville sheet, Cal.).

Though the contrasts pointed out above are not sharp and decisive in all cases, much of the more typical dune topography can be identified with considerable certainty on topographic maps. Such areas are likely to show very few outcrops of bedrock, and are particularly unfavorable to structural determinations, either on the map or in the field.

Coastal dunes often occur on spits, hooks, or barrier beaches, and may be seen to advantage on the Sandy Hook (N. J.) or Rehoboth (Del.) sheets.

Crescentic dunes are especially well developed on the Moses Lake (Wash.) sheet. A group of such dunes, with the crescents all turned in one direction, gives a clue to the prevailing wind, which blows in the direction pointed by the horns of the crescent.

The Lakin sheet (interval 20 feet) also furnishes excellent illustrations of isolated elevation and depression contours, on which numbers have not been printed, and gives point to the problems described on pages 15–16. For example, in secs. 20 and 29, T. 25 S., R. 37 W. is a large depression contour lying on the slope between the 3,080- and 3,100-foot lines. It, therefore, should be read as the 3,080 contour. The area within it, but not within the smaller enclosed contours, is, therefore, below 3,080, but above 3,060 feet. From such an area one goes up to the small hills, with closed 3,080-foot contours, and down into still lower depressions marked by the 3,060-foot depression contours. Within one such inner depression in the N. ½ sec. 29 are three small hills, encircled by 3,060-foot curves.

Most of the depressions, shown by a single hachured contour, may range from a foot or two in depth to nearly 40 feet, and occasional ones with two depression contours exceed 20 feet but cannot be as deep as 60 feet. For example, study the depression shown in the NW. cor. sec. 4, T. 26 S., R. 35 W., shown by two contours, the 2,980 and the 2,960. The rim of this depression might be as high as 2,999 feet, and its bottom as low as 2,941 feet, in which case it would be nearly 60 feet deep. Or its rim might not be over 2,981, and its bottom might be 2,959 feet, in which case it would not be much over 20 feet in depth.

A peculiar type of ridge and depression topography on a very small scale is to be noted on the Bellaire (Tex.) sheet. It must be realized that the contour interval on this map is only 1 foot, so that few of the depressions are over 2 feet deep, and probably none of them more than 3 feet. Many of these depressions are entirely or partly surrounded by a low rim, in several

cases showing as a crescentic closed contour. Except for the size and the depth, they resemble breached craters (p. 61), but, of course, in this area have nothing whatever to do with vulcanism. While no evidence has thus far been received, it seems more than probable that these represent actual wind-scoured depressions, the sand and soil being caught by the grass as a low ridge about the rim.

Most of the dunes on the Lakin sheet are shown by a single closed contour. The height of such dunes above the plain on which they rest may vary between limits of a foot or two up to nearly 40 feet. A few, with two contours, may not greatly exceed 20 feet in height, or may be nearly 60 feet above the base on which they rest, the same principles of interpretation being used as for the depressions (pp. 15–16 and 28). There are doubtless many dunes and depressions in the area which do not "catch a contour", and are, therefore, not mapped.

The Lakin sheet also shows strikingly the contrast between stream-sculptured topography north of the Arkansas River, and dune topography to the south.

Sand dunes are especially common along certain portions of the Atlantic coast, from Massachusetts to Florida, particularly on sand bars; also along the south and east end of Lake Michigan; elsewhere east of the Mississippi they are not generally well developed. They are also common along parts of the Gulf Coast of Texas. Interior dune areas are widespread in the western half of the Great Plains, especially along the Platte and Arkansas valleys. In the Cordilleran region, many of the arid and semiarid interior basins contain them in abundance. They are also common on parts of the Pacific coast.

Additional maps illustrating sand dunes

Yuma, Cal.-Ariz.	Camp Clarke, Neb.
Monterey, Cal.	Kearney, Neb.
Cumberland Island., Ga.	Wyndemere, N. D.
Kingsley, Kan.	Coos Bay, Ore.
Pratt, Kan.	Siltcoos Lake, Ore.
Cherry Ridge, Mont.	Lopena Island, Tex.

Tarida Ranch, Tex.

TOPOGRAPHY RESULTING FROM THE WORK OF GLACIERS

Erosional Features—Mountain or Alpine Glaciation

Maps

Mt. Lyell, Cal.	Kintla Lakes, Mont.
Mt. Shasta, Cal.	Mt. Hood, Ore.-Wash.
Mt. Whitney, Cal.	Hayden Peak, Utah-Wyo.
Yosemite Valley, Cal.	Mt. Adams, Wash.
Hamilton, Mont.-Idaho.	Mt. St. Helens, Wash.
Chief Mountain, Mont.	Cloud Peak, Wyo.

True mountain or Alpine glaciation is chiefly the result of glacial ice streams occupying, locally, preexisting valleys carved by normal stream erosion. These valleys are not infrequently profoundly modified by glacial erosion, and, although all such erosion must necessarily have its complement of deposition, mountain regions, mapped, as a rule, with a 50- or 100-foot interval, do not commonly show the presence of moraines, except in so far as the many lakes are the result in part of glacial damming, as well as of glacial scour. In such regions, however, it is chiefly glacial erosion that stamps on the topography its most striking features.

Existing mountain glaciers are to be seen on the Mt. Shasta (Cal.), Mt. Hood (Ore.-Wash.), Mt. Adams (Wash.), Mt. St. Helens (Wash.), Mt. Lyell (Cal.), and Chief Mountain (Mont.) sheets. The topographic results of mountain glaciation are especially well shown on the Hamilton (Mont.-Idaho), Chief Mountain (Mont.), Cloud Peak (Wyo.), Mt. Lyell (Cal.), Mt. Whitney (Cal.), Hayden Peak (Utah-Wyo.) sheets, and the Yosemite Valley (Cal.) map.

The Hamilton (Mont.-Idaho) sheet affords an excellent contrast between a non-glaciated mountain area in the southeast corner, and a glaciated mountain range in the west half of the map. The lack of glaciation in the southeast is probably the result of the lower elevation, resulting not only in less severe cold, but also—and probably more important—in a much smaller precipitation.

The features to be contrasted specifically in the topographic detail of the two regions are:

1. The presence of lakes in the glaciated area, and their absence in the southeastern region that has not been glaciated.

2. The striking difference in the nature of the valley heads. Those in the southeast area (*cf.* Rye Creek, in the extreme southeast corner of the map) consist of many small, minutely branching headwater ravines. On the contrary, many of those in the western glaciated area have their source in broad, steep-sided, flat-floored amphitheaters known as *cirques*, carved largely by glacial plucking. The head of Blodgett Creek (W. cent. rect.) and the valley head just east of El Capitan (SW. rect.) are particularly good examples.

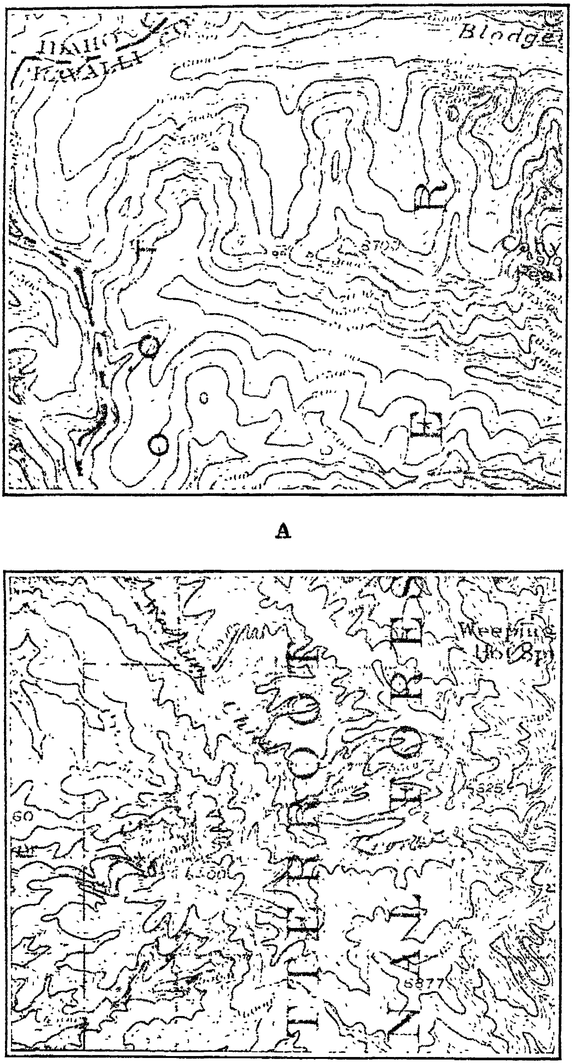
3. The U-shape, in cross-section, of the valleys in the western area, as contrasted with the V-shape in the southeast portion. Flat bottoms and steep sides are well shown on White Sand Creek (NW. rect.) and Blodgett Creek (W. cent. rect.). Such flat bottoms are strikingly rare in the non-glaciated portion.

4. The relation of the tributaries to the main stream is different in the two areas. In the southeast, the junctions are dominantly *accordant*, that is, the profile of the tributary becomes flatter as the main stream is reached, and at the junction the two are about on a level. In the glaciated area, on the other hand, the normal profile of the tributary steepens notably in its lower course, just at the point where it enters its trunk valley, the junction being accomplished by a fall or rapid, shown by the closer crowding of the contours across that part of the tributary.

Such *hanging valleys*, as they are called, result from the greater glacial erosion of the main valleys, leaving the tributaries *discordant*. The two north-side tributaries of White Sand Creek (NW. rect.) show this feature particularly well, the contours across the tributaries being much more crowded near the trunk stream, and more widely spaced above.

The contrasts just described are, perhaps, made somewhat clearer by a study of Fig. 6.

The western area in the Hamilton (Mont.-Idaho) quadrangle had probably reached submaturity (pp. 90–94) in the



A

B

Fig. 6.—Portions of the Hamilton topographic sheet, showing contrast between glaciated (A) and non-glaciated (B) mountain topography. *(U. S. Geol. Survey.)*

erosion cycle, by normal stream drainage, before being glaciated. The glacial modification has resulted in superimposing on this submature topography certain youthful features, most striking of which are the numerous lakes—an otherwise abnormal feature in a region so well dissected. The numerous rapids and falls of the hanging tributaries also constitute features of early youth imposed on a region of a distinctly later stage.

The Chief Mountain (Mont.) sheet shows a region much more profoundly scoured by glacial action than the preceding map. In the east central rectangle are examples of divides almost cut through by the opposing headward erosion of cirques on opposite slopes. A still later stage in cirque cutting is shown on the Hayden Peak (Utah-Wyo.) sheet, in which the original upland has almost wholly disappeared, its remnants showing as narrow sinuous walls between opposing cirques. The boundary between Summit and Wasatch counties follows such a wall through the central and east central rectangles. On the Kintla Lakes (Mont.) sheet, a similar intercirque wall has been completely eaten through by headward cirque erosion, leaving a series of pyramidal peaks (E. cent. rect.) with curved faces which represent what is left of the old amphitheater walls.

The contrast between glaciated and non-glaciated mountain topography is again beautifully shown on the Mt. Whitney (Cal.) sheet, the Sierra Nevada showing lakes, cirques, and hanging valleys in great perfection, features not to be seen in the Inyo Mountains.

The elevation at which mountain glaciation is now occurring, and has occurred in the past, should be estimated on the various sheets. It is commonly related to latitude, precipitation, and degree of exposure to sun or to moisture-laden winds. The only important areas of mountain glaciation, past or present, known in the United States are in the Cordilleran region, west of the one hundred fifth meridian and chiefly north of the thirty-fifth parallel. It is in these areas that cirques, hanging valleys, and other features of mountain glaciation may be expected.

Additional maps showing mountain glaciation

Bridge River, B. C.	Custer, Idaho.
Sandon, B. C.	Nyack, Mont.
Kaweah, Cal.	Philipsburg, Mont.
Mt. Goddard, Cal.	Gilbert Peak, Utah-Wyo.
Mt. Morrison, Cal.-Nev.	Uinta, Utah.
Anthracite, Colo.	Glacier Peak, Wash.
Georgetown, Colo.	Mt. Baker, Wash.
Leadville, Colo.	Mt. Ranier National Park, Wash.
Mt. Jackson, Colo.	Skykomish, Wash.
Rocky Mountain National Park, Colo.	Afton, Wyo.
Silverton, Colo.	Freemont Peak, Wyo.

Depositional Features—Continental Glaciation

Maps

Holtville, Cal.	Lansing, Mich.
Monmouth, Ill.	Milford, Mich.
Lehigh, Iowa.	Brainard, Minn.
Lakin, Kan.	Green City, Mo.
Passadumkeag, Maine.	Plainfield, N. J.-N. Y.
Boston and vicinity, Mass.	Rochester, N. Y.
Holyoke, Mass.-Conn.	Weedsport, N. Y.
Durand, Mich.	Sun Prairie, Wis.

Whitewater, Wis.

Although continental glaciers erode, and that powerfully, the commoner forms which can be recognized on the map are depositional.

The most widespread single type of deposit is doubtless the *ground moraine.* It is usually characterized by lakes, swamps, depressions, lack of apparent relation between streams and higher lands, and usually by a sparing distribution of low, rounded, irregularly distributed hills. The Lansing (Mich.) sheet affords an excellent example, deposited so recently as to have undergone but little modification by running water. The distribution of the drift is probably but little affected by bedrock, and there is nothing whatever on the map to indicate the stage of the erosion cycle (pp. 90–94) in preglacial time, though it is known from drill records that it was much more advanced in the cycle than the present extremely youthful features would indicate. The super-

imposed youth has completely obliterated the earlier more mature topography. This should be contrasted with the Holyoke (Mass.-Conn.) sheet, which is also overspread widely, but thinly, with ground moraine. In the latter sheet, however, the early relief was too great to be so completely obliterated, so that the maturity of the preglacial dissection is obvious, though superimposed on it are certain youthful features, chiefly lakes.

A topography like that on the Lansing sheet is hardly to be mistaken even on the map alone for anything but the result of continental glaciation. On the other hand, the older drift sheets, which have been completely drained and moderately dissected (Monmouth sheet, Ill.; Lehigh sheet, Iowa; and Green City sheet, Mo.) give scant evidence of their origin from the topographic map alone.

A special phase of ground moraine is the extensive development of oval or elliptical hills, from 10 to 100 feet or more in height, and from a few rods to a mile or two in length, with their longer axes parallel to the direction of ice movement. Such hills are called *drumlins*, and consist of unsorted glacial deposits, with usually no sign of a solid bedrock core. The Weedsport (N. Y.), Sun Prairie (Wis.), and Boston and vicinity (Mass.) sheets show this kind of hill in typical development. The common statement that drumlins have their steeper slopes in the direction from which the ice came is shown, by an inspection of the above sheets, to have a very large number of exceptions. To prove or disprove this statement, one should count all the drumlins on a given sheet, listing them in three columns headed *north steeper*, *south steeper*, and *about equal;* no two men, of course, will get quite the same results, but this furnishes a fair way to approach the problem.

Frontal or *terminal moraines* constitute one of the particularly striking features of glacial topography. Conditioned by a more or less considerable stillstand of the ice front, so that the débris resulting from the melting accumulated as a distinct line of hills, a belt of moraine topography usually consists of a rather definite, but very irregular, range of smaller and larger knobs, among

which are many depressions, the result of irregular deposition, or of the melting of buried ice blocks.

A very pronounced morainal belt runs diagonally across the Brainard (Minn.) sheet, and others across the Milford (Mich.) quadrangle, and the Whitewater (Wis.) sheet. Such moraines are usually associated with abundant lakes and make rather a definite ridge, the hills commonly grouped in such a way as to show a number of small prominences on a larger base. This serves in some measure to discriminate moraine topography from sand-dune areas such as are seen on the Lakin (Kan.) sheet, in which lakes are usually of the temporary type, if present at all, and in which there is usually a greater number of smaller and more isolated hills. Dune ridges may, however, rather closely simulate moraine topography, as on the Holtville (Cal.) sheet.

As the glaciers melted, the glacial waters, charged with an excessive amount of sediment, laid down stratified or partly stratified sands, gravels, and silts known as *glacio-fluvial deposits.* Of these, *outwash plains* bordering the outward edge of moraine areas are the most extensive. Such plains are best recognized from their relation to the morainal belt, and are characteristically pitted (from the melting of buried blocks of ice). A very good example is the plain south of the moraine belt on the Whitewater (Wis.) sheet. Outwash plains frequently merge, on their outer edge, into *valley trains*, but these cannot ordinarily be recognized as such on topographic maps. The associated depressions are commonly termed *kettles.*

Streams flowing in channels under the ice build up long, narrow, winding ridges known as *eskers.* Such ridges are to be seen on the Lansing (Mich.) sheet, in secs. 2 and 11, T. 3 N., R. 2 W.; on the Durand (Mich.) sheet, in sec. 23, T. 5 N., R. 5 E.; and on the Passadumkeag (Maine) sheet, on which the two ridges known as Enfield Horseback and Hoytville Horseback are unusually fine examples.

Irregular hillocks of stratified sand and gravel known as *kames* are deposited by glacial waters near the margin of the ice. Such hills, particularly if associated with moraine topography, as they

frequently are, cannot readily be identified from the map alone. Such a group of kames, south of the city of Rochester on the Rochester (N. Y.) sheet, might quite readily be mistaken for rock hills projecting through the drift; except, perhaps, that they do not show any asymmetry from the scouring effect of the ice on their north slopes. On the Plainfield (N. J.-N. Y.) sheet, a group of kames occurs just southeast of Milltown (NE. rect.). Their nature is by no means clear from the map alone, however.

Areas that are deeply and widely overspread by glacial deposits commonly have their bedrock structure largely or completely masked, so that no relation exists between structure and topography.

The chief areas of continental glaciation in the United States lie north of the Ohio and Missouri rivers from New England and New Jersey west to Montana. A large ice lobe also overspread part of the state of Washington. It is only in these areas that one may look for extreme development of the features described in the foregoing sections.

Additional maps showing various phases of continental glaciation

Ground moraine little modified
Barrington, Ill.
Crystal Falls, Mich.
Minneapolis, Minn.
Rockford, Minn.
Childwold, N. Y.
Neshkora, Wis.
Waukesha, Wis.

Drumlins
Hartford, Conn.
Auburn, N. Y.
Clyde, N. Y.
Fulton, N. Y.
Palmyra, N. Y.
Sodus Bay, N. Y.
Beaverton, Ont.
Waterloo, Wis.
Watertown, Wis.

Ground moraine considerably dissected
Fort Dodge, Iowa.
Pella, Iowa.
Colchester, Ill.
Gillespie, Ill.
Chillicothe, Mo.
Canton, Ohio
Fostoria, Ohio

Terminal moraines
Marthas Vineyard, Mass.
Ann Arbor, Mich.
Schoolcraft, Mich.
Three Rivers, Mich.-Ind.
Pillager, Minn.
Edgeley, N. D.
Wyndemere, N. D.
Hartford, Wis.
St. Croix Dalles, Wis.-Minn.

Eskers

Fowlerville, Mich. (secs. 1 and 12, T. 2 N., R. 2 E.; also secs. 6, 7, 18 and 19, T. 3 N., R. 3 E.).
Rives Junction, Mich. (secs. 8, 17, 20, 28, and 29, T. 1 N., R. 1 E.).
St. Francis, Minn. (secs. 8 and 16, T. 33 N., R. 25 W.).
Beaverton, Ont. (E. ½ SE. rect.).
Kirkfield, Ont. (just southeast of Cameron Lake, SE. rect.).

Glacial Diversion of Drainage

Maps

Cordova, Iowa-Ill.
Syracuse, N. Y.
Elmira, N. Y.-Pa.

The most common effect of glaciation on drainage is the production of lakes and swamps by the blocking of the old drainage lines, or by the scouring out of new basins. Such results have already been shown in the two preceding sections. Only glacial diversions that leave well-marked abandoned channels will be considered in this section.

Stream piracy alone may result in abandoned valleys; nevertheless, such features are by far more common in and bordering glacial regions, as a result of obstruction of streams either by ice or by outwash, forcing the streams to seek new courses. Although it is not always possible from the map alone to refer such changes definitely to glacial action, it is frequently possible even from the map, without field studies, to outline essentially the nature of the diversions that have occurred, and in many cases to conclude that the changes are at least indirectly related to adjacent glacial phenomena. In this, however, one's general knowledge of the glacial and physiographic history of the region involved is a factor.

Striking modifications of drainage are shown on the following sheets. On the Elmira (N. Y.-Pa.) quadrangle the most striking features are: first, the gorge of Chemung River immediately south and west of Elmira, the narrowness of which is in sharp

contrast to the width of the Chemung Valley to the east and west; and, second, the wide, open valley from Big Flats to Horseheads and thence to Elmira, not now occupied by any single continuous stream, but connected at each end with the Chemung Valley, which it notably resembles in width.

It is obvious at once that this wide, open, abandoned valley was the former course of Chemung River, and that the Chemung gorge is a more recent course of the stream, the narrowness of which results chiefly from the fact that it has had less time to widen out, not that the rock is necessarily harder.

There are two common types of glacial diversion which might result in an abandoned valley of this sort. One of these might have been produced by the actual temporary presence of glacial ice in a portion of the valley, raising the water level so that it flowed across the ridge to the south. Since there is little visible evidence of glacial occupation of this area, one could point to no proof that the above is the correct explanation.

Another possible interpretation is that in preglacial time a low saddle occurred along the course of the present gorge portion of Chemung River, at a time when that stream occupied the broader valley to the north. Glacial outwash, in the form of valley trains coming down the streams entering Chemung River from the north, gave that stream more load than it could remove, and its channel was silted up higher than the low saddle just postulated, at which stage it naturally took the easier course.

A very similar case occurs on the Cordova (Iowa-Ill.) quadrangle. The extremely narrow portion of the Mississippi Valley at Leclair (SW. rect.) and the wide abandoned lowland to the east, both ends of which connect with the river, and the width of which matches the rest of the present valley, prove the Mississippi once flowed through the abandoned valley, the gorge at Leclair being more recent. Other drainage changes, somewhat more obscure, are also suggested on the Cordova sheet.

Another type of abandoned channel near and within the borders of glaciation does not represent former courses of existing streams, but marks temporary spillways of glacial waters

during the melting and retreat of the great ice sheet. Such is believed to be the origin of the open channel southeast of Syracuse (Syracuse sheet, N. Y.) between Onondaga and Butternut creeks, a channel about 100 feet above the present level of both creeks, with no stream now occupying it. Such a history is usually not obvious from the map alone, but confirmatory evidence on the ground may be sought in the relations of such channels to abandoned lake beaches, and similar phenomena.

Glacial diversions of drainage may be expected not only in the areas of immediate glaciation, but in bordering non-glaciated regions subject to silting of streams by glacial outwash.

Other maps showing abandoned stream courses, either of preglacial streams that have been diverted, of extraglacial streams that have been partly silted up, or of temporary spillways for glacial waters, are listed below. It is frequently not possible to decipher the full history from the map alone.

Additional maps showing stream diversion related to glaciation

Wheaton, Yukon Terr., Can.	Pingree, N. D.
Central City, Ky.	Hamilton, Ohio.
Battle Lake, Minn.	Barrie, Ont.
Kremlin, Mont.	New Effingham, S. D.-N. D.
Batavia, N. Y.	Peever, S. D.-Minn.
Naples, N. Y.	Beverly, Wash.
Nunda, N. Y.	Connell, Wash.
Penn Yan, N. Y.	Malaga, Wash.
Tully, N. Y.	Moses Lake, Wash.
Watkins Glen, N. Y.	Red Rock, Wash.
Wayland, N. Y.	Van Zandt, Wash.

Baraboo, Wis.

FEATURES RESULTING FROM THE WORK OF WAVES

The shoreline, where land and water meet, is being continuously modified by the attack of waves. Before it is possible, however, to evaluate this work, consideration must be given to the character of the shore on which the waves direct

their attack. Since a shoreline results from the coming to rest of the water level against the land, its initial character will depend chiefly on the nature of the land surface. If this is smooth, the shoreline will be straight; if rugged, it will be notably irregular.

It is obvious that an area above water is subject to erosion, which may tend to make it more rough, whereas an area under the sea is subject to deposition, which tends to smooth out its unevenness. The lowering of the land may bring the water to rest against an irregular surface of erosion, and result in deep bays, numerous islands, and depths that change notably from place to place. These are characteristic initial features of *shorelines of submergence.* On the other hand, if the land is raised or the water lowered, the new water surface comes to rest against even ocean bottom, producing a straight shoreline, with few or no offshore islands, and with a very gently sloping and regular offshore profile. Such are the initial characteristics of a *shoreline of emergence.* Another type results from neither emergence nor submergence, but from the building forward of an outwash or delta plain into a body of water. This type is known as a *neutral shoreline.* Combinations of any two or more of the above types, as a result of successive changes, may be termed *compound shorelines.*

If a coastal region were submerged deeply for a very short time then raised slightly, it would, of course, in one sense be emergent; but it is obvious that its major features would still be those imposed on it by its earlier movement, and since the terminology of the shore cycle, like that of the land cycle, has its chief value in presenting to us a concrete picture, it should still be described as a shoreline of submergence. Likewise, if a coastal region were uplifted a considerable amount, but did not remain at that level long enough for any appreciable dissection of the land mass, then were lowered by an amount less than the preceding uplift, it would, in a sense, have been drowned, but its features would clearly be those of a shoreline of emergence, and it should be so classed.

Features of Submergent Shorelines

Maps

Cayucos, Cal.	Bay City, Mich.
Cape Henlopen, Del.	Deerwood, Minn.
Rehoboth, Del.	Wealthwood, Minn.
Boothbay, Maine.	Winnepesaukee, N. H.
Casco Bay, Maine.	Sandy Hook, N. J.-N. Y.
Moosehead Lake, Maine.	Sandusky, Ohio.
Drum Point, Md.	Coos Bay, Ore.
Boston and vicinity, Mass.	Erie, Pa.
Falmouth, Mass.	Edisto Island, S. C.
Marthas Vineyard, Mass.	Ocosta, Wash.
Nantucket, Mass.	Port Angeles, Wash.

The Boothbay (Maine) sheet may be taken as a typical shoreline of submergence. The long narrow bays, which are not straight enough, or free enough of islands, to have resulted entirely from glacial scour below sea level, represent old valleys into which the sea has backed as the land surface was depressed. The offshore islands are the tops of hills not yet completely drowned, but lowered sufficiently to be cut off from the mainland. Since the zone immediately offshore was once rugged land, water depths are very irregular, as strikingly exemplified on the Casco Bay (Maine) sheet, on which the submerged contours are shown in blue. This should be contrasted with the gently sloping offshore profile of the Cape Henlopen and Rehoboth (Del.) sheets.

Shorelines entirely comparable to those of Maine may be formed by the damming of a drainage course by any cause, artificial or natural, so that the waters back up into the tributary valleys. Such conditions obtain in many regions as a result of glacial obstruction of old drainage lines (Winnepesaukee sheet, N. H., and Moosehead Lake sheet, Maine).

Assuming, now, an indefinite length of time without further changes of level, the chief factor to modify the Boothbay shoreline will be the work of waves and accompanying currents in cutting away exposed headlands, filling bays, and rendering the

shoreline straight. On the Boothbay sheet the waves have done very little to accomplish this change, and we may, therefore, speak of such a shoreline as being in *early youth.* On the other hand, a shoreline of emergence would be very straight in early youth, so that in discussing the work of waves we must keep clearly in mind the type we have to begin with. It must also be kept in mind that the stage of the shore cycle is measured in the ratio of *wave work* already done to that still to be accomplished; and may be quite independent of the stage of the erosion cycle of a region (pp. 89–96), which is measured in terms of the *work of its rivers.* On the Boothbay sheet, for example, the degree of dissection of the *region* by its rivers is somewhere about mature (the lakes being youthful features glacially superimposed). But, in spite of the maturity of its *dissection by streams* (p. 91), its shoreline as measured in terms of wave work is still very youthful.

The amount of modification depends, in part, on the force of the waves, which varies with the degree of exposure or protection; in part, on the hardness or the softness of the rock materials on which the waves are acting; and, finally, in part, on the duration of the wave attack.

Comparing now the map of Boston and vicinity (Mass.) with the sheet just studied, interesting contrasts are to be noted. The embayed character of the shoreline about Boston is such as to give evidence of at least moderate drowning. The attack of the waves has already initiated the straightening process by actively cutting away parts of certain islands, such as Great Hill and Strawberry Hill (S. cent. rect., E. sheet), and has apparently completely reduced other islands, as at Nixes Mate (SW. rect., E. sheet). This material has been worked over into bars, as at Lynn Beach (NW. rect., E. sheet) and Nantasket Beach (S. cent. rect., E. sheet), which connect former islands with the mainland. In a few instances, bays have been isolated or partly isolated, as at Phillips Beach (N. cent. rect., E. sheet) or Straits Pond (S. cent. rect., E. sheet). In spite of this modification, however, offshore islands and irregularity predominate, and the shoreline

is still in the earlier part of youth. This coastal area is no more exposed than that at Boothbay, and has probably not been subject to wave erosion any considerably greater length of time, the fact that it is more modified being due chiefly to the less resistant character of the rocks.

Turning now to the Marthas Vineyard (Mass.) sheet, we see a notable difference. This coastal area, though it was produced chiefly by the building forward of an outwash plain (a neutral shoreline, p. 51), has clearly been somewhat dissected, and moderately submerged, as shown by its notably embayed character. The waves have attacked the headlands, and built bars across the bays until the shoreline on the south is practically straight. Wave work has accomplished more than in the two preceding cases, and the shoreline may be spoken of as submature, or just passing out of late youth into early maturity. This stage is characterized by ponds, many of them without connection with the sea, others into which considerable streams flow, maintaining outlets. Soft rocks and exposed position are chiefly responsible for its more rapid maturing. The shoreline cannot be said to be fully mature until it has retreated past the heads of at least the greater part of the existing bays.

A still later stage is to be seen on the Drum Point (Md.) sheet. This is clearly a shoreline of submergence, as shown by the embayed character of Patuxent River and its tributaries. Nevertheless, that portion in the central and northwest rectangles is well cliffed, with scarcely a single embayment. Obviously, this part, as a result of its more exposed position, has been cut back completely past all its embayments, and may be said to be fully mature, whereas that part along the Patuxent is protected from excessive wave attack, and is still distinctly not past early to middle youth, since few of the headlands are cliffed, and few of the bays cut off by bars.

Since not until a shoreline has retreated past all its former embayments is it said to be fully mature, there does not appear to be any definite line of demarcation between this and any possible later stages, so that we do not, in the present state of

our knowledge of shore processes, refer to late mature or old shorelines.

The character of a shoreline of submergence will depend upon the degree of dissection, the relief, and the amount of depression of the preexisting land mass. If the area is in the early youth of its stream cycle (p. 90), with but few valleys and with broad and flat divides, and the amount of depression is slight (Rehoboth sheet, Del.), there will be a few bays with broad headlands, showing only minor indentations, and with rather uniform offshore depths. If the region is maturely dissected (p. 91) and of bold relief, and the drowning considerable (Boothbay sheet, Maine), there will be deep, long, branching embayments, narrow, bold headlands, many rocky offshore islands, and a great irregularity of depth in the offshore area. If the region is in old age, with very low rolling divides, very broad, flat valleys, and occasional monadnocks (p. 92), the shore will show broad, deep embayments, gently sinuous but subdued headlands, and occasional rocky offshore islands. No case of just this type seems to be shown on available maps.

During the process of straightening a shoreline of submergence many wave-built forms are developed. The material cut by the waves is drifted by *littoral currents* that do not follow the embayments but pass along in nearly straight lines into deeper water, where the load is dropped, building a long narrow deposit with one end attached to the shore, the free end projecting into deeper water. Such a deposit is known as a *spit*, a good example of which is shown partly enclosing Sandusky Bay on the Sandusky (Ohio) sheet. An especially fine illustration is also afforded by Ediz Hook, on the Port Angeles (Wash.) sheet. On the Ocosta (Wash.) sheet, such a spit is seen partly enclosing North Bay. Outward and inward currents resulting from wind and tidal action tend to scour the end of such a spit, and build secondary deposits transverse to it. On the seaward side, as a result of more active wave attack, and deeper waters, such deposits either grow slowly or are removed, whereas in the shallower, protected bays they remain, the tendency usually being for such spits to

turn toward the land, as the one on the Ocosta sheet is clearly doing. When the turn is especially noticeable, the spit is usually called a *hook* (Sandy Hook sheet, N. J.-N. Y.) or *recurved spit.* Such wave-made deposits, starting as spits, may grow across the mouths of bays, nearly or quite isolating them. Morrow Bay (Cayucos sheet, Cal.) has been thus modified by a *bay mouth bar.* Other good cases of bays partly or quite cut off are shown on the Falmouth (Mass.) sheet, and on the south shore of Nantucket (Nantucket sheet, Mass.), also on the south shore of Marthas Vineyard (Marthas Vineyard sheet, Mass.). The growth of such spits into bay mouth bars may sometimes, as at Coos Bay (Coos Bay sheet, Ore.), deflect streams for some distance, parallel to the coast. Spits or bars may tie islands to the mainland, as on the sheet of Boston and vicinity (Mass.), the bar then being known as a *tombolo,* and the island as a *tied island.* The direction in which a spit points indicates the dominant direction of littoral current, though temporarily such direction may be reversed.

On a shoreline that is growing forward by additions of wave- and current-transported sand more rapidly than it is being cut back by wave action, successive parallel or nearly parallel low ridges of sand, generally known as *beach ridges,* are fairly common. The nearly parallel curved ridges on Presque Isle (Erie sheet, Pa.), separated by swampy belts, are probably of this origin, though they may be modified by dune drifting. Similar beach ridges are shown in rather typical development on the Bay City (Mich.) sheet, with long narrow depressions between that resemble those resulting from oxbows partly silted up. The tendency toward low parallel ridges on the Edisto Island (S. C.) sheet also suggests old beach embankments. Ridges of somewhat similar appearance on the Deerwood and Wealthwood (Minn.) sheets, along the north shore of Mille Lacs Lake, may be beach ridges or *ice-push ridges,* produced by the expansive effect of lake ice overriding the shore.

The coasts of New England, Chesapeake Bay, Puget Sound, and San Francisco Bay are our best examples of notably submerged shorelines, though most of these when studied in detail

also show evidences of uplift. Some drowning is to be seen locally on the Great Lakes, and on other parts of our eastern and western coasts.

Additional maps showing features characteristic of submerged shorelines

Youthful shorelines of submergence

Pronounced embayment	*Offshore islands*
Point Reyes, Cal.	San Francisco, Cal.
Bath, Maine.	Duncan, B. C.
Petit Manan, Maine.	Deer Isle, Maine.
Choptank, Md.	Monhegan, Maine.
St. John, N. B.	Swan Island, Maine.
Staten Island, N. J.-N. Y.	Vinalhaven, Maine.
Oak Harbor, Ohio.	Passage Island, Mich.
Maumee Bay, Ohio-Mich.	Kelleys Island, Ohio.
Hoquiam, Wash.	Snohomish, Wash.

Irregular offshore depths

Columbia Falls, Maine.
Great Wass Island, Maine.
Portland, Maine.
York, Maine-N. H.

Submature to mature shorelines of submergence

Prince Frederick, Md.
St. Marys, Md.-Va.
Ontario Beach, N. Y.
Pulaski, N. Y.
Heathsville, Va.-Md.

Features of Emergent Shorelines

Maps

Cape Henlopen, Del.	Sandy Hook, N. J.-N. Y.
Rehoboth, Del.	Sea Isle, N. J.
Atlantic City, N. J.	Islip, N. Y.
Asbury Park, N. J.	Ridgeway, N. Y.
Barnegat, N. J.	Euclid, Ohio.
Long Beach, N. J.	Lopena Island, Tex.

Saltillo Ranch, Tex.

An emergent shoreline, under ordinary circumstances, is characterized by straightness and by a gently sloping offshore profile. The simplest cases available for study are probably to be seen on the Great Lakes (Ridgeway sheet, N. Y., and Euclid sheet, Ohio) and in portions of Texas (Saltillo Ranch and Lopena Island sheets). It so happens, however, that, although much of our Atlantic coast has been emergent in recent times, and shows the typically gentle profile which is normally to be expected, there are few areas that have not undergone at least moderate recent drowning and embayment, producing compound shorelines. This results in a combination of moderate embayment with gentle offshore profile, as on the Cape Henlopen and Rehoboth (Del.) sheets.

The initial state of an ideally simple shoreline of emergence would be very straight, with such shallow depths that only the smallest waves could be active at the land's edge. Here, in early youth, they would cut a low cliff called the *nip*. Larger waves, breaking offshores, tend to heap up the sand in a ridge parallel to the shoreline, which, as soon as it rises above low-water stage, is known as an *offshore* or *barrier bar* or beach. Good illustrations of the earliest stage are hard to find, but there are many fine examples of the stage in which the barrier or offshore bar has formed. Among these the Long Beach (N. J.) sheet is exceptionally good.

As soon as such a bar becomes established, the waves, continually attacking its seaward face, cut away the sand, part of which is thrown on or over the bar, to be washed down its back slope, so that the bar is constantly retreating landward. A shoreline of emergence is considered youthful until the bar has been driven back to the original mainland, when maturity is attained. In our present state of knowledge, there are not, apparently, sufficient distinctions to justify trying to divide youth in definite stages other than the initial state, early youth characterized by the nip only, and youth (middle to late youth undifferentiated), marked by the presence of the offshore bar. The Long Beach and Barnegat (N. J.) sheets may, therefore, be considered as

representing typical cases of youth on an emergent shoreline. On the next sheet to the north (Asbury Park, N. J.), the bar has been driven back so that much of it rests against the mainland, though bits of lagoon area still intervene. This may be classed as submature, whereas the southermost part on the Sandy Hook (N. J.-N. Y.) sheet may be considered to have reached full maturity. It is true that the shoreline on both the Asbury Park and the Sandy Hook sheets shows indisputable evidence, by its embayment, of moderate recent drowning; nevertheless, the gentle and regular offshore profile of emergence is clearly indicated by the offshore bar, and its relation to the Barnegat sheet is clear.

The mature stage of an emergent shoreline is straight and cliffed, as in early youth when the nip is present, the essential difference consisting in the character of the offshore profile. In case the cliff is the nip of early youth, the water is not deep enough for the larger waves to break at the land's edge. If, with ordinary waves, there is a surf line some distance from land, the shoreline is young; if, on the other hand, the largest waves break at the cliff line, it is mature. It may not always be possible to distinguish the two cases on a map. It may also be difficult to distinguish, on the map, a mature shoreline of submergence from one of emergence, though the latter is likely to be the more regular, since it was straight to begin with. Neither is it possible, in our present state of knowledge of shore processes, to draw any really useful distinctions of stage, beyond full maturity, so that we do not ordinarily consider late maturity or old age in discussing shoreline evolution.

The area between the offshore bar and the mainland, well shown on the Atlantic City (N. J.) sheet, is termed a *lagoon*. Waves and tidal currents ordinarily maintain *tidal inlets* connecting the lagoon with the open ocean, such as Absecon and Brigantine inlets (Atlantic City sheet). The deep channels opposite these inlets, known as *thoroughfares*, are scoured by constantly reversing currents, which tend to build *tidal deltas*, at each end of the channel. The external delta is vigorously

attacked by waves and currents, which remove its material, so that it seldom shows on a map, but in the quiet water of the lagoon these forms are well shown, as at the inner end of Main Channel, opposite Absecon Inlet.

Barrier beaches not infrequently show *offset*, as on the Atlantic City and Sea Isle (N. J.) sheets, the bars becoming progressively nearer shore in the direction in which the *dominant* littoral current moves. In some cases, the ends actually *overlap* (Islip sheet, N. Y.).

Many shorelines of emergence show old beach ridges or abandoned wave-cut terraces well above the reach of the waves at the present time. Such abandoned shorelines, which constitute one of the most striking evidences of emergence, will be considered at more length in a later section (p. 53).

The best examples of emergent shorelines occur in New Jersey, Georgia, Florida, and Texas and on the Great Lakes. Even these are modified locally by recent drowning. Many other shorelines, such as those of Virginia, California, etc., show strong evidences of both emergence and submergence.

Other maps showing emergent shorelines

Nome, Alaska.	Vermilion, Ohio.
Hueneme, Cal.	Cape May, N. J.
Cedar Creek, Del.	Dennisville, N. J.
Palm Valley, Fla.	Great Egg Harbor, N. J.
Conneaut, Ohio-Pa.	Little Egg Harbor, N. J.

Features of Neutral Shorelines

Maps

Cat Island, La.	Timbalier, La.
East Delta, La.	Brooklyn, N. Y.
Fort Livingston, La.	Hempstead, N. Y.
Forts, La.	Riverhead, N. Y.
Quarantine, La.	Sag Harbor, N. Y.

Mt. Vernon, Wash.

Shorelines that result from neither emergence nor submergence, but by the building forward of alluvial deposits into a body of water, are spoken of as neutral.

The outwash plain on the south shore of Long Island, if unmodified by uplift or depression, would illustrate this type. Such a shoreline is moderately straight to begin with, and behaves much as an emergent one. Whether it will develop an offshore bar or not will depend largely on the steepness of the offshore profile. The south shore of Long Island is fringed by offshore bars with the usual lagoons and other features comparable to those of New Jersey, and, like the New Jersey region, shows slight embayment from recent depression. These features are shown particularly well on the Brooklyn, Hempstead, Riverhead, and Sag Harbor (N. Y.) sheets.

On the other hand, the delta of the Mississippi, although showing a neutral shoreline, is, on account of the growth of its delta fingers (ends of distributaries), much more irregular in outline (East Delta sheet, La.) than the Long Island outwash plain. There is much the same tendency to cut back headlands, and build spits, hooks, and mouth bay bars as on a submerged coast. In this way Barataria Bay (Fort Livingston sheet, La.) is being isolated by Grand Isle and Grand Terre Island. A similar process is to be seen on the south shore of the Quarantine (La.) sheet. A typical spit is shown on the Cat Island (La.) sheet.

On the other hand, the offshore profile is neither excessively steep nor notably irregular, and, on some points along the delta, "reefs" analogous to offshore bars are being formed, such as Robinson Reef (East Delta sheet, La.), Timbalier and East Timbalier Islands (Timbalier sheet, La.), and Bird Islands (Forts sheet, La.).

This neutral shoreline, therefore, shows both submergent and emergent characteristics. In addition, there are small islands of peculiar origin, known as mud lumps (East Delta sheet, La.), supposed to be produced by flowage of semifluid clay as a result of the loading on the delta surface, much as such flowage occurs

in building railway embankments across swampy areas. The mud lumps are relatively evanescent features, rapidly cut away by wave attack.

The most extensive neutral shorelines in the United States are the outwash plain of Long Island and Marthas Vineyard, and the delta of the Mississippi. Other smaller deltas occur, as along the shores of Puget Sound (delta of Skagit River, Mt. Vernon sheet, Wash.).

Other examples of neutral shorelines

Karquines, Cal.	Barnstable, Mass.
Montpelier, Idaho-Wyo.-Utah.	Babylon, N. Y.
Bonnet Carre, La.	Fire Island, N. Y.
Cheniere Caminada, La.	Moriches, N. Y.

Features of Compound Shorelines

It has been shown in a previous section (p. 41) that, regardless of the direction of the latest movement of a shoreline, it is classified as emergent or submergent according to whether it shows exclusively or overwhelmingly the one or the other set of features. If, however, the effects are so nearly balanced that it shows easily recognized features of both types, as, for example, a moderate embayment, together with typical offshore bars, it is called a compound shoreline. This type usually results from emergence, with moderate dissection of the land mass, and very slight recent depression, producing embayment, but still preserving the gentle offshore profile of emergence necessary to the formation of bars. Most of the shorelines of emergence and several of the neutral ones cited show features of submergence, and some of the submergent shorelines show features of emergence, as, indeed, would most of them if mapped in sufficient detail.

Additional maps showing compound shorelines

Rehoboth, Del.	Marthas Vineyard, Mass.
Green Run, Md.-Va.	Asbury Park, N. J.
Ocean City, Md.-Del.	Sandy Hook, N. J.-N. Y.

Abandoned Shorelines

Maps

Anaheim, Cal.	Chesaning, Mich.
Downey, Cal.	Carson Sink, Nev.
Holtville, Cal.	Cienega Springs, N. M.
La Jolla, Cal.	Oak Orchard, N. Y.
Las Bolsas, Cal.	Ridgeway, N. Y.
Redondo, Cal.	Berea, Ohio.
San Pedro, Cal.	East Cincinnati, Ohio.
Santa Anna, Cal.	Euclid, Ohio.
Ventura, Cal.	Mentor, Ohio.
Cambon, Fla.	Oberlin, Ohio.
Fernandina, Fla.-Ga.	Coos Bay, Ore.
Hilliard, Fla.	Fairview, Pa.
Lawtey, Fla.	Salt Lake, Utah.
Macclenny, Fla.-Ga.	Stockton, Utah.
Mayport, Fla.	Toole Valley, Utah.
Palm Valley, Fla.	Kilmarnock, Va.
Boulogne, Ga.-Fla.	Matthews, Va.
Everett City, Ga.	Morattico, Va.
Folkston, Ga.-Fla.	Tappahannock, Va.
Moniac, Ga.-Fla.	Urbanna, Va.
Nahuanta, Ga.	New Kent, Va.
St. Charles, Mich.	Williamsburg, Va.

Moses Lake, Wash.

As the land and the water change their relative levels, the shoreline features are either brought below water level, as in drowning, or are lifted above it, as in emergence. If they are submerged, they are largely concealed from study, and almost wholly from representation on ordinary topographic maps. Submerged terraces or beach ridges are, therefore, rarely called to our attention. On the other hand, uplift brings them into a very conspicuous position, where they afford one of the most striking evidences of recent emergence. Such features will in time, of course, be completely cut away by subaerial agencies, but as long as they are preserved they afford especially valuable and convincing evidence of the nature of shore change.

Such abandoned beaches and wave-cut terraces are very prominent along the shores of the Great Lakes, where it has

been rather a lowering of the water level, as new and lower outlets were exposed by the retreating ice, than true uplift that has brought these forms into such conspicuous relations as they now occupy.

In Ohio, wave-cut cliffs are especially well shown on the Oberlin, Berea, Euclid, and Mentor sheets. A very persistent cliff is North Ridge (NE. rect., Oberlin sheet), which can be traced east on to the Berea quadrangle. It is also a prominent feature on the Mentor sheet, but, as it is traced westward on the latter area, it is seen to approach more closely to the successively higher beaches, until on the next sheet to the west (Euclid) it is scarcely distinguishable from them. On the Mentor sheet, in addition to the cliff being cut at present, there is North Ridge, then the unnamed ridge formed by the 720- and 740-foot contours, and the higher and larger one with its base at about 780 feet. The highest of these is, of course, the oldest, and they mark in descending order successive stages in the lowering of the water level in the glacial Great Lakes. The amount of lowering at any particular time is measured by the difference in elevation of successive shorelines. It must be remembered, however, that some of the old shorelines will not show on all maps, because of poor mapping, or the use of an interval too large to show the minor ridges.

Associated with these old shorelines are likely to be abandoned beach ridges (p. 46). The long, narrow, closed 730-foot contours along the road about 2 miles east of North Amherst (W. cent. rect., Oberlin sheet) probably mark old beach ridges. A similar occurrence along Middle Ridge (E. cent. rect., Oberlin sheet) is shown by the closed contour at North Ridgeville, and it is doubtless this feature which is responsible for the deflection of the small stream, which is also deflected by Sugar Ridge, just to the south.

A wave-cut cliff is shown on the Fairview (Pa.) sheet, just south of the New York, Chicago and St. Louis Railroad, and a beach ridge along the closed loops of the 700-foot contour followed by the road east and west of Fairplain (SE. rect.).

An excellent example of a beach ridge is shown along the Ridge Road, in the south portion of the Ridgeway and Oak Orchard (N. Y.) sheets. The device of an intermediate contour (dotted) is used to show the ridge where it is not high enough to "catch" a regular contour (p. 16).

What appear to be similar beach ridges are shown on the Chesaning (Mich.) sheet (cent. and E. cent. rects.), also on the St. Charles (Mich.) sheet, at about 610 feet (N. cent. and W. cent. rects.).

Along the Atlantic coast, the region about Chesapeake Bay, although extensively drowned and embayed, shows at least one remarkably perfect terrace of recent uplift that can be easily recognized on available topographic maps. The marine cliff shows in the north central rectangle of the Kilmarnock (Va.) sheet as a step between the eastern plain just below 20 feet, and the western upland around 80 feet. This escarpment can be traced west and northwest up Rappahannock River (Urbanna, Morattico, and Tappahannock sheets, Va.) several miles, where it might be mistaken for a normal alluvial terrace (p. 71), were it not that it can be traced continuously at essentially the same elevation into the cliff facing Chesapeake Bay, on the Kilmarnock (Va.) sheet.

The same escarpment can be traced southwest across the Matthews and Williamsburg (Va.) sheets and up York River, and its two main forks, Mattaponi and Pamunkey rivers, entirely across the New Kent (Va.) sheet, where again, were it not for its relation to the main seaward-facing cliff, it might be mistaken for a normal stream terrace.

The recently uplifted plain at about 10 to 20 feet on the east side of the Matthews (Va.) sheet is but little dissected and is clearly in early youth (p. 90) of the normal stream-erosion cycle, whereas the upland shown in the northwest part of this map, and much of the Williamsburg sheet, at an elevation of about 75 feet, is much more dissected, being perhaps in middle or later youth of the normal cycle. The contrast results from adding a fringe of more recent lowland by uplift, and illustrates what is known as a *topographic unconformity*.

It must not be overlooked that, although this area shows evidence in its elevated marine cliff of rather recent emergence, the pronounced embayment also affords clear proof of drowning. That the larger bays antedate the emergence is clear from the fact that the marine terraces extend far up their courses. The small embayments in the youthful fringing plain east of the escarpment (Kilmarnock and Matthews sheets) are probably the result of a drowning more recent than the making of the cliff, since it would seem impossible to have produced so uniform a submarine platform between these rather closely spaced and numerous bays without filling them.

Very fine examples of marine terraces are to be seen along the Georgia-Florida line. Attention might first be called to the nature and the regularity of the present beach, as shown on the Palm Valley (Fla.), Mayport (Fla.), and Fernandina (Fla.-Ga.) sheets, with the lagoons on the landward side, and a striking parallelism of ridge and swamp areas, apparently controlled by minor beach ridges.

The first conspicuous elevated marine cliff now has its base at about 20 to 30 feet above sea level, and can be traced quite readily across the Everett City (Ga.), Nahuanta (Ga.), Boulogne (Ga.-Fla.), Hilliard (Fla.), and Cambon (Fla.) sheets.

The second conspicuous cliff line has its base at about 75 to 100 feet, and can be traced with ease across the Folkston, Moniac, Macclenny (Fla.-Ga.), and Lawtey (Fla.) sheets. Just west of this cliff is Trail Ridge, rising from about 150 feet on the north of the Folkston sheet to over 200 feet at the south end of the Lawtey sheet, some 70 miles farther south, and showing a gentle back slope into the Okefenokee swamp, which seems to be held in by a beach ridge at the crest of the marine cliff.

Many very fine marine terraces are also known on the Pacific coast, but, owing to the larger interval employed on most of the maps of that region, and also to the fact that these terraces are narrower and in some cases more dissected, they are not, in general, as conspicuous features of the available topographic maps. An especially good group of maps to show these features

are the Santa Anna, Anaheim, Las Bolsas, Downey, San Pedro, and Redondo (Cal.) sheets. Along the coast of the San Joaquin Hills (Santa Anna sheet) there is a very distinct terrace at about 75 to 100 feet, with marine cliffs above and below. Between Abalone Point and Two Rock Point (SE. rect.) is a very sharp promontory on which is a closed 100-foot contour marking what appears to have been a stack, when the sea level was at the base of the cliff rising above the 100-foot line.

At that stage of the history of the region, much of the Santa Anna plain must have constituted the broad Los Angeles embayment in the coast, running well back towards Anaheim (Anaheim sheet). Into this, the Santa Anna, San Gabriel, and Los Angeles rivers discharged, building the delta that now constitutes this plain. The isolated hill Los Cerritos (Downey sheet) was then probably an offshore island. The present San Pedro Hills (San Pedro and Redondo sheets) also constituted another offshore island, on which the 100-foot wave-cut bench is very pronounced. There are suggestions of other terraces on the slopes of these hills. The low ridge between Inglewood (Redondo sheet) and Los Cerritos (Downey sheet) strongly suggests an old bay bar or spit.

A particularly interesting case is to be seen on the La Jolla (Cal.) sheet. North of Mission Valley is a dissected platform at an elevation of about 400 feet. On this upland are several ridges running slightly west of north. A conspicuous one is enclosed by the 400-foot contour, just east of the fifteen minute meridian between the fifty and fifty-five minute parallels. Several closed loops of the 325-foot line west of Tecolote Valley (SW. rect.) show another. Still another is marked by several small loops of the 400-foot contour, on the east side of the same canyon, and can be traced north to Soledad Valley (W. cent. rect.). These two latter ridges are clearly responsible for the sharp bend in Tecolote Valley, and its large east-side tributary, and have much the appearance of ridges produced by westward-dipping beds (p. 149). Another similar ridge is marked by the closed 425-foot line in the northwest part of the south

central rectangle, north of Murray Canyon. These are said to be old beach ridges on a wave-made platform. Their effect on drainage is quite similar to that cited on the Coos Bay (Ore.) sheet (p. 46), and on the Oberlin (Ohio) sheet (p. 54).

One of the higher terraces on the California coast is shown on the Ventura sheet, the 500-foot level being very conspicuous near Punta Gorda (W. cent. rect.).

Many fine, abandoned shoreline features are to be seen about the numerous basins in Utah and Nevada formerly occupied by lakes where none now exist, or by lakes more extensive than the residual salt-water bodies now occupying them. Unfortunately, much of that region is either not mapped at all, or covered only by the old reconnaissance sheets of small scale and large contour interval, on which the detail of old shore features is quite overlooked. A very fine example of such an old wave-cut cliff is to be seen in the north central rectangle of the Stockton (Utah) sheet, from Stockton northeastward. On this map, with the $1/62{,}500$ scale and the 50-foot interval, the shoreline is very conspicuous. Contrasting this with the older Toole Valley (Utah) sheet, which includes the area of the Stockton sheet, but on the scale of $1/250{,}000$ and with an interval of 250 feet, one is impressed with the importance of the larger scale, the smaller interval, and the better quality of mapping on the Stockton sheet.

On the Salt Lake (Utah) sheet, there appears to be a wave-made terrace, just north of Provo and just east of Spanish Fork, of sufficient magnitude to show, even with the 250-foot interval employed on this map. The long, narrow, somewhat curved ridge east of Carson Sink (Carson Sink sheet, Nev.) suggests an old beach ridge, and the ribbon-like ridge in the north central rectangle of the Holtville (Cal.) sheet is a shoreline feature of the Salton Basin. The gently curved ridge on the Cienega Springs (N. M.) sheet (T. 34 S., R. 20 W.) also strongly suggests a beach ridge, and its northeastward extension as an escarpment resembles a wave-made terrace, though no information is at hand to verify the interpretation.

River terraces (p. 71) may frequently closely resemble those produced by wave work. In general, they are to be distinguished by the fact that a wave-made terrace usually faces either a body of water, such as a lake (Oberlin sheet, Ohio) or the ocean (Kilmarnock sheet, Va.), or at least a coastal plain (Everett City sheet, Ga.) or dried-up lake bed (Cienega Springs sheet, N. M.). A true alluvial river terrace, on the other hand, commonly borders a river, at least in fragmentary form, for considerable distances on both sides (East Cincinnati sheet, Ohio). In rarer cases, marine cliffs may face a river that was formerly a bay (Morattico and Tappahannock sheets, Va.), in which case they are distinguished only by tracing them continuously and at accordant levels, into undoubted marine cliffs, facing the ocean. River terraces also commonly slope in the direction of stream flow. Marine and lake terraces are level, when formed, though they may be tilted during their uplift. The edges of river terraces are not uncommonly marked by meander scarps (p. 75) of former meanders of the river that produced them (NW. rect., Moses Lake sheet, Wash.).

Elevated shorelines are common along the Atlantic and Pacific coast, on the shores of the glacial Great Lakes and other marginal lakes of the glaciated district, and on the shores of many of the so-called Pleistocene lakes of the semiarid and arid Great Basin.

Other maps showing abandoned shorelines

Beach ridges	*Wave-cut cliffs*
Oceanside, Cal.	Calabasas, Cal.
Cumberland Island, Ga.	Camulos, Cal.
Egypt, Ga.	Brooklet, Ga.
Elsie, Mich.	Perrington, Mich.
Saline, Mich.	Westfield, N. Y.
Dunkirk, N. Y.	Ashtabula, Ohio.
Chardon, Ohio	Vermilion, Ohio.
Perry, Ohio.	Girard, Pa.
Edisto Island, S. C.	Smithfield, Va.
Wadmelaw Island, S. C.	Toano, Va.

FEATURES RESULTING FROM VULCANISM

Although vulcanism is reflected in a great variety of topographic features, many, such as the irregular surfaces and depressions on lava flows and ash beds, are usually so small as not to be represented on ordinary topographic sheets. Others, such as lava-capped mesas, hogbacks produced by dipping sills or flows, and related forms, are not to be distinguished on contour maps from analogous forms produced by alternating hard and soft sedimentary rocks.

Cones and Craters

Maps

Flagstaff, Ariz.
Bachellor Valley, Cal.
Clear Creek, Cal.
Honey Lake, Cal.
Lassen Peak, Cal.
Marysville Buttes and vicinity, Cal.
Mt. Lyell, Cal.
Mt. Shasta quadrangle, Cal.
Mt. Whitney, Cal.
Shasta sheet, Cal.
Island of Oahu, Hawaii.
Monadnock, N. H.
North Conway, N. H.-Maine.
Crater Lake National Park, Ore.
Mt. Hood, Ore.-Wash.
Bellaire, Tex.
Abajo, Utah.
Henry Mountains, Utah.
La Sal, Utah.
Mt. Adams, Wash.
Mt. Ranier National Park, Wash.
Mt. St. Helens, Wash.

Of the striking and characteristic types, *cones* and *craters* are most readily identified on topographic sheets. Among the cones of first magnitude, which would not ordinarily be confused with other forms, and which show almost ideal symmetry, the following are especially fine examples: Mt. Shasta (Shasta sheet and Mt. Shasta quadrangle, Cal.), Mt. Adams (Mt. Adams sheet, Wash.), Mt. Hood (Mt. Hood sheet, Ore.-Wash.), Mt. St. Helens (Mt. St. Helens sheet, Wash.), Mt. Ranier (Mt. Ranier National Park sheet, Wash.).

Marysville Buttes (map of Marysville Buttes and vicinity, Cal.), and San Francisco Mountain (Flagstaff sheet, Ariz.) are somewhat dissected cones. These may be confused, on topographic maps, with some of the larger laccolithic peaks, such as Mt. Ellsworth, or Mt. Pennell (Henry Mountains sheet,

Utah), the Blue (Abajo) Mountains (Abajo sheet, Utah), or the La Sal Mountains (La Sal sheet, Utah.).

In comparing these various sheets, the wide divergence in scales and intervals must be kept in mind. Were these same dissected laccolithic peaks mapped in more detail, they would almost without exception show inward-facing minor escarpments, resulting from the outward dips (dome) of the adjacent sedimentary rocks (p. 164), a situation which may also be shown in volcanic cones when considerably dissected (Marysville Buttes and vicinity, Cal.). Rarely will ordinary monadnocks (Monadnock sheet, N. H.) tower as isolated symmetrical peaks to such great heights above the surrounding country as do these major volcanic peaks. Confirmatory evidence of cone structure is often to be seen in associated minor peaks with craters.

The minor volcanic peaks (Flagstaff sheet, Ariz.), unless marked by craters, are not always sufficiently different from many buttes of ordinary erosion (Clear Creek, Cal.; Bachellor Valley, Cal.; and North Conway sheet, N. H.-Maine) to make possible any positive discrimination from contour maps alone. However, such isolated knobs as Shaffer Peak (Honey Lake sheet, Cal.) and the one on the Lassen Peak (Cal.) sheet, east of the fifteen minute meridian between the thirty and forty-five minute parallels, are so strikingly symmetrical as strongly to suggest volcanic cones.

The presence of a depression in the top of the peak usually gives definite proof of its volcanic character. Of course, the most notable crater in the United States is Crater Lake (map of Crater Lake National Park, Ore.). A small crater also shows in the minor cone known as Wizard Island, and an excellent *breached crater*, marked by crescentic contours partly surrounding a depression, is to be seen in the northeast rectangle, at Timber Crater. Shastina (Mt. Shasta quadrangle, and Shasta sheet, Cal.) is another excellent example of a breached crater. Others are shown on the Flagstaff (Ariz.) sheet, two of them (N. cent. rect.) occupied by crater lakes.

Many fine examples of cones with craters are shown on the United States Geological Survey's topographic map of the

Island of Oahu, Hawaii. Diamond Head, Kaau, Koho, and Punch Bowl craters, east of Honolulu, are among the most conspicuous.

Mt. Wing (cent. rect., Flagstaff sheet, Ariz.) affords a good opportunity to apply the principles of numbering contours discussed on pages 12–16 and 28–29. The depression contour lies between elevation contours 8,400 (closed round) and 8,500 (heavy closed, crescentic). From an elevation above 8,400 but below 8,500, the first contour crossed in going down into the depression is the 8,400 line, which is the elevation of the hachured contour.

Another very interesting case on the Mt. Lyell (Cal.) sheet is to be noted in sec. 19, T. 1 N., R. 27 E. This cone, clearly, has a breached crater, in which a group of smaller cones has been built, leaving only two small crescentic depressions in the original crater. This affords another somewhat complicated case of numbering contours. The two crescentic elevation contours, portions of the rim of the old crater, lie on a topographic surface between the 6,800- and 6,900-foot lines, as do also the two crescentic depression contours. From an elevation above 6,800, but below 6,900 feet, one goes down into the depression to the hachured lines numbered 6,800 feet, and up to the crescentic hills marked by the 6,900-foot contour. The closed elevation contour between the two crescentic depressions also lies next above the 6,800-foot line, and is, therefore, 6,900 feet, so that the three very small closed curves within it represent the 7,000-foot contour.

Cirques (p. 31) may, under rare conditions, somewhat resemble breached craters (Tulainyo Lake, S. cent. rect., Mt. Whitney sheet, Cal.). Ordinarily, they do not show depression contours within the amphitheater, though, as in this case, they may. Neither do breached cones always show such depression contours (N. cent. rect., same sheet). Both may be occupied by lakes. The outlet of a cirque is, ordinarily, as broad as the cirque itself, that of a breached crater is usually narrower than the width of the crater. This also finds its exception in the cases just cited on the Mt. Whitney sheet. Perhaps more distinctive is the fact that breached craters usually have the crescent as the hill

crest, the crater occupying an isolated peak; whereas a cirque is more often down the slope of a ridge or peak, some distance below its crest, and not enclosed by doubly crescentic loops. More rarely a crater may occupy a position well down on a slope, as in Kaau Crater (east of Honolulu, contour map of Island of Oahu, Hawaii Territory). In this case, however, the breach is too narrow to admit of its being interpreted as a cirque.

Another type of depression which remarkably resembles breached craters is to be noted on the Bellaire (Tex.) sheet. These are probably due to wind work as explained on page 28.

Cones and craters are not known east of the Rocky Mountain foothills, and are most abundant in New Mexico, Arizona, California, Oregon, and Washington. Features topographically resembling them in the eastern United States must be assigned to other causes.

Other maps showing cones with craters

Chiricahua, Ariz.-N. M. (Tps. 21 and 22 S., Rs. 30 and 31 E., Ariz.).
Bishop, Cal. (S. cent. rect.).
Honomu, Hawaii (Kauku Crater, cent. rect.).
Honuapo, Hawaii (SW. rect.).
Kohala, Hawaii (chiefly E. cent. rect.).
Waipio, Hawaii (Puu Ahia Crater, W. cent. rect., and many others).
Henry, Idaho (sec. 14, T. 5 S., R. 41 E.; also sec. 9, T. 7 S., R. 41 E.).
Silver Peak, Nev.-Cal. (sec. 27, T. 1 S., R. 39 E.).
Mt. Riley, N. M. (numerous in W. ½ of sheet).
Diamond Lake, Ore. (Timber Crater, SE. rect., and Crater Butte, NE. rect.).
Mt. Adams, Wash. (crescentic hills in Tps. 6 and 7 N., R. 11 E.).

Dikes

Elmoro, Colo.
Walsenburg, Colo.
Spanish Peaks, Colo.
Jemes, N. M.
Wingate, N. M.

Dikes can be identified on topographic sheets only in so far as they are harder or softer than the enclosing rocks. If softer, they yield more easily to erosion, and form valleys. No examples of this are known to show on topographic maps. On the other hand, if the dike is more resistant, it may be etched into pronounced

relief. In such a case, the resulting long, narrow, straight ridge may closely resemble one produced by the edge of a tilted layer of hard sedimentary rock (p. 149), and in many instances it is quite probable that the two could not be told apart. If, however, all the remainder of the topography indicates horizontal or homogeneous (pp. 126–129) rocks, such ridges may be interpreted as dikes.

The Spanish Peaks region (Spanish Peaks, Walsenburg, and Elmoro sheets, Colo.) is the best area known to show dikes clearly on topographic maps. A very striking one occurs in the N. ½ T. 32 S., R. 66 W., in the central rectangle of the Spanish Peaks sheet, crossing Frio Canyon at the letter "a" of the word "Canyon". Since the contour interval is 100 feet, its height is considerable. It does not show as a continuous wall, but as a series of long narrow hills in nearly perfect alignment. Many other such dikes show on this map.

Radiating from East and West Spanish Peaks, in the northwest part of the sheet, are numerous ridges, many of which are merely normal stream divides. Others, however, that are especially straight, narrow, and sharp, such as the one crossing the letter "s" of the word "Apishapa" in the S. ½ T. 31 S., R. 67 W., the one along the name "Gulnare" in the E. ½ T. 31 S., R. 66 W., and the one on the letter "M" of "Mitotes" in the W. ½ of the same township, are clearly dikes radiating from the Spanish Peaks; while the ridge carrying the boundary between Huerfano and Las Animas counties, T. 30 S., Rs. 66 and 67 W., is probably not dominantly controlled by a dike. The radial arrangement of dikes about a volcanic center is rather common and affords confirmatory evidence that the ridges are not steeply tilted sedimentary beds.

On the Elmoro (Colo.) sheet, in T. 30 S., R. 63 W., in a region that certainly does not otherwise indicate high folding, is another narrow dike-formed ridge. An even better example shows in T. 32 S., R. 63 W.

The Walsenburg (Colo.) sheet shows two X-shaped ridges (S. line. S. cent. rect.) interpreted as intersecting dikes, since

they are not of a type that might result from folding or faulting.

Long, narrow ridges, very similar in aspect to those just described as dikes, occur about 3 miles east of Gallup (Wingate sheet, N. M.), and can be traced north of the railroad about 5 miles, where they turn abruptly east into an escarpment which can be followed to the east edge of the map, clearly marking a dipping bed of rock (p. 149). In other instances the distinction is less easy to make. The ridge in the northwest rectangle of the Jemes (N. M.) sheet is, according to Darton,[1] a "hogback of steeply tilted . . . strata".

Dikes are widely distributed, but east of the Mississippi River few are known to show on topographic maps in sufficiently distinctive form to be positively identified.

Other maps showing dikes

Apishapa, Colo. (NE. ¼ cent. rect. and NW. ¼ SW. rect.).
Huerfano Park, Colo.
Lamy, N. M. (W. cent. rect. and probably NW. rect.).

FEATURES RESULTING CHIEFLY FROM DIASTROPHISM

Maps

Mt. Trumbull, Ariz.	San Mateo, Cal.
Mt. Whitney, Cal.	Lida, Cal.-Nev.
Point Reyes, Cal.	Kiefer, Okla.
Priest Valley, Cal.	Monterey, Va.-W. Va.
Quincy, Wash.	

Although many familiar features result from the combined action of diastrophism and erosion, there are relatively few diastrophic features, unmodified by the gradational agents, that can be identified as such with any certainty on topographic sheets.

Recent faulting not infrequently results in a visible *fault scarp*, such as the one designated as the "Earthquake Fault", in Tps. 15 and 16 S., R. 36 E., in Owens Valley (Mt. Whitney sheet, Cal.). This scarp does not "catch a contour", and is indicated by hachures. If a scarp has been completely erased by plana-

[1] Personal communication.

tion, and then reproduced by erosion of hard and soft beds in juxtaposition, it may more properly be spoken of as a *fault-line scarp*. Grand Wash Cliffs and Hurricane Ledge (Mt. Trumbull sheet, Ariz.) are either fault, or more probably fault-line, scarps, but there is nothing by which they can be identified as either with certainty, on the sheet. Babcock Ridge (Quincy sheet, Wash.) and the dominant escarpment passing through Kiefer (Kiefer sheet, Okla.), both of which result purely from erosion on alternating hard and soft beds, are quite as regular, and there do not seem to be any satisfactory criteria for distinguishing the two types, from topographic form alone. Purely erosional escarpments, it is true, usually occur only in stratified rock consisting of alternating hard and soft beds, and a very straight scarp in rocks, the general topography of which suggests crystalline masses, is more than likely to be the result of faulting (Point Reyes sheet, Cal.).

A fault which has had its scarp completely wiped out by erosion may, with the proper arrangement of hard and soft beds and further erosion, develop a new one facing in the same way as before (a *resequent fault-line scarp*) or in a direction opposite to the earlier one (an *obsequent fault-line scarp*) (see pp. 185–189).

Faults occasionally produce long, narrow lowlands, sometimes as a result of more effective erosion along the zone of fracturing and brecciation, but more often, perhaps, as a result of narrow dropped blocks between two closely spaced faults. Such a *rift valley* is well shown on the San Mateo (Cal.) sheet, occupied by Crystal Springs and San Andreas Lakes. It marks the trace of the San Andreas fault, movement along which resulted in the San Francisco earthquake of 1906. Parallel rifts of this sort may produce a type of trellised drainage (Priest Valley sheet, Cal.) usually much less intricate and closely spaced than that developed on alternating hard and soft folded beds (Monterey sheet, Va.-W. Va., pp. 103, 129 and 191–192).

Folding, unmodified by erosion, would result in ridges on the sites of anticlines and valleys on the sites of synclines. This situation is usually greatly modified by erosion, so that not

uncommonly the anticlines are finally marked by valleys and the synclines by mountains (pp. 172 and 175). There are, however, in the Great Basin area, many undrained intermontane basins without outlets which are either down-folded or down-faulted. Although change from humid to arid climate might result in changing a basin (not a lake) with outlet to one without, by allowing talus slopes to block an earlier outlet channel, it is probable that many of the deeper of these undrained intermontane lowlands are primarily structural, especially one like Eureka Valley (Lida sheet, Cal.-Nev.), the lowest point of which is more than 1,500 feet lower than the lowest notch in its rim.

Because diastrophic features unmodified by erosion are so very rare, and because the effects of erosion on diastrophic features so commonly result in forms which give clues to structure, any further consideration of the topics briefly mentioned in this section will be deferred to the section on "Relation of Land Forms to Structure" (p. 123).

FEATURES RESULTING FROM THE WORK OF RUNNING WATER

Running water produces land forms of two types, those resulting chiefly from its erosive activity, and those brought about by the deposition of this eroded material. It is chiefly in the erosion forms produced by running water that structure can be read, so that attention will first be directed to those forms resulting from deposition, and the erosion forms will be considered in the section immediately preceding the "Relation of Land Forms to Structure".

Deposits Made by Running Water

Fans, Cones, and Piedmont Alluvial Plains.—

Maps

Benson, Ariz.	Iuka, Miss.-Ala.-Tenn.
Cucamonga, Cal.	Cienega Springs, N. M.
McKitterick, Cal.	Cooperstown, N. Y.
Mt. Whitney, Cal.	El Paso, Tex.
San Antonio, Cal.	Wellington, Utah.

Streams with high gradients in mountainous areas, emerging into valleys or onto foothill plains, have their velocity so diminished that much of their sediment is dropped, building up a cone-shaped or fan-shaped deposit of débris closely analogous to a delta, except that it is built on land rather than in the water. Such a deposit, if it is very steep, is called an *alluvial cone*, if flatter an *alluvial fan*, there being no definite line of demarcation between the two forms. A typical fan is shown in the west central rectangle of the Cucamonga (Cal.) sheet, opposite the mouth of San Antonio Canyon. It is indicated in the way the contours bend outward from the mountains in smooth curves, opposite the canyon mouth, indicating a fan-shaped accumulation of débris, which the stream has not been able to remove. The fan slope is greater nearer the mountains where the coarser material has been dropped, reaching over 200 feet to the mile; whereas south of Ontario, where only the finer sediment could be carried, it is less than 100 feet. The growth of the fan has forced Thompson Creek, which is smaller, and can build less rapidly, back into an abnormal position against the base of the mountains.

A heavily laden stream flowing across the surface of such a fan keeps choking up its own channel until it is forced to break out into a new line of flow, thus forming the numerous *distributaries*, or discharge channels shown as branching brown strips extending south from the mouth of the canyon. Not infrequently some of the channels become *braided*, or interlocking, as in the east central rectangle.

The contours, as they cross the larger of the brown areas, bend very abruptly upward toward the mountains, then turn squarely across the brown strip and bend as abruptly back, thus indicating steep-walled *arroyos*, or miniature canyons, countersunk into the surface of the fan. On this sheet, none of these arroyas are as deep as a contour interval (50 feet) since at no point does the loop of one contour extend up within the loop of the next. About 25 feet seems to be the maximum depth.

The stream in San Antonio Canyon, shown in solid blue as having a permanent flow, totally disappears through subsurface drainage in the upper and coarser part of the fan, but is again forced out as springs or seeps farther from the base of the range, either where the materials are finer and the conditions for subsurface flow less favorable, or, more probably, where a barrier of older impervious rock comes close to the surface.

There are several other fans on the sheet, which, because of their close spacing and resultant interference, have so lost their individual identity that they have coalesced to produce a *piedmont alluvial plain*, or *mountain apron*. The surface of this plain, as yet almost untouched by erosion, is in strong contrast with the maturely dissected (p. 91) upland to the north, a contrast described by the term *topographic unconformity* (pp. 55 and 92–93).

Piedmont alluvial plains which have grown towards each other from two or more mountain ranges are not uncommonly termed *bolsons* in the Southwest, and the El Paso (Tex.) special map illustrates a large bolson plain, the growth of which has partly buried and isolated a number of foothill peaks west of the Hueco Mountains.

The center of such a plain may be occupied by a temporary or *playa* lake (McKitterick sheet, Cal.), and on some such lakes, now abandoned, the old shorelines may be traced (Cienega Springs sheet, N. M.).

Where the material from one mountain range is greatly in excess of that from the other, the alluvial slopes are very unequally developed. This is well shown on the Mt. Whitney (Cal.) sheet, Owens River being crowded to the east side of the valley by the heavier alluviation from the Sierra Nevada.

Such slopes or mountain aprons may be exceedingly regular, as on the San Antonio (Cal.) quadrangle, or may surround isolated mountain masses in beautifully symmetrical curves (Benson, Ariz.).

Piedmont alluvial plains may finally become much dissected, as at the base of Book Cliffs (Wellington sheet, Utah), so that the asymmetry of some of the erosion remnants (sec. 9, T. 14 S., R. 11 E.) may give the impression of structural escarpments (p. 154), whereas they really represent initial dip.

The best fans, cones, bolsons, and piedmont alluvial slopes are to be found in the arid West, where most of the rainfall in the mountains is lost in the desert basins by seepage or evaporation, so that all the sediment accumulates in the basin. The most notable examples occur in western Texas, New Mexico, Arizona, Utah, Nevada, and California, bordering and flooring the great intermontane basins.

Although numerous fans and cones can be seen in almost any locality, most of those east of Mississippi River are so small that they do not show on available topographic sheets. On the west side of Chester Valley (N. ½ cent. rect. and SE. ¼ N. cent. rect., Cooperstown sheet, N. Y.) are two beautifully symmetrical ridges built into the main valley by small west-side tributaries, either as fans, or as deltas into a former lake connected with glacial damming. There does not seem to be any way, from the map alone, to decide which these may be, though their position upstream from a pronounced moraine across the valley suggests the latter interpretation. Quite similar in appearance are very small fans on the Iuka (Miss.-Ala.-Tenn.) sheet, between the road and railroad in the W. ½ sec. 23, T. 3 S., R. 15 W., and in the W. ½ sec. 32, T. 2 S., R. 15 W.

Additional sheets showing fans, cones, and piedmont alluvial plains

San Simon, Ariz.-N. M.	Tonopah, Nev.
Colusa, Cal.	Big Hatchet Peak, N. M.
Pasadena, Cal.	Playas, N. M.
San Bernardino, Cal.	Hood Spring, Tex.
Soledad, Cal.	Van Horn, Tex.
White Mountain, Cal.-Nev.	Fish Springs, Utah.

Malaga, Wash. (along Moses Coulee).

Alluvial Terraces.—

Maps

Diamond Creek, Ariz.	Tarboro, N. C.
Flathead Coal Area, B. C.	Cohoes, N. Y.
San Bernardino, Cal.	Canal Dover, Ohio.
Soledad, Cal.	East Cincinnati, Ohio.
Yuma, Cal.-Ariz.	Beaver, Pa.
Jonesboro, Ill.-Mo.	Fowlkes, Tex.
Marseilles, Ill.	Malaga, Wash.
Renault, Ill.-Mo.	Guyandot, W. Va.-Ohio.
Mountain Home, Idaho.	Ravenswood, W. Va.-Ohio.

It not infrequently happens, sometimes from one cause, sometimes from another, that a stream, once its valley is well established, fills that valley with alluvium to a considerable depth, ranging from a few feet in the usual case to a few hundred feet in rarer instances. The stream may then once more reverse its activity and intrench itself in the alluvium it has deposited. During the process of intrenching it usually leaves well-defined benches, sometimes at more than one level, sometimes on one and sometimes on both sides of the valley, often more or less fragmentary. These are known as alluvial terraces.

One of the commonest causes of such valley filling seems to have been the excessive sediment contributed by the melting of the continental ice sheet to the streams in the area bordering the ice front. Climatic changes and changes of level may produce essentially the same reversals of stream activity.

Alluvial terraces of the usual type are very well shown on the Tarboro (N. C.) sheet, especially on the west side of Tarr River (E. cent. rect.), also on the Fowlkes (Tex.) sheet, on the north side of Wichita River (SW. rect.).

Terraces related directly or indirectly to glaciation are especially well developed along much of the course of Ohio River and its tributaries. On the Beaver (Pa.) sheet, the most striking level is at about 770 to 780 feet, though a 740-foot level is evident opposite the village of St. Clair (SE. ¼ NE. rect.). On the Guyandot (W. Va.-Ohio) sheet, the most pronounced terrace is at about 560 feet, which is several feet above the recorded

high-water mark of 551 feet. On the Ravenswood (W. Va.-Ohio) sheet there is a well-marked level at about 600 feet, and a very well preserved remnant of a higher one just above 640 feet (opposite Millwood, cent. rect.). On the East Cincinnati (Ohio-Ky.) sheet, Newport, Dayton, California, Coney Island Resort, Melborn, and Ross are located on a pronounced terrace.

The Cohoes (N. Y.) sheet shows exceptionally good examples of similar features near the junction of the Hoosic and Hudson rivers. Several levels occur in the north half of the central rectangle. There is one south of the river, just above the 140-foot contour, another above the 180-foot line, another above 220, and north of the river another above 240, and a broad one above 340. There are probably few available maps that show a succession of terraces as fine as this.

As shown on the above sheet, the terrace levels may not correspond on opposite sides of the valley, especially where there are several levels and the terraces are fragmentary. A single simple terrace is more likely to show the same level on both sides (East Cincinnati sheet, Ohio).

A very good example of a broad, simple terrace occurs along the north side of Sandy River, on the Canal Dover (Ohio) sheet (cent. rect.) just above 960 feet. Another, often cited as an especially good example, shows on the older edition of the Marseilles (Ill.) sheet, mapped with 10-foot contours. On the revised edition the detail of the map as a whole is much better, but the 20-foot interval used has rendered the terrace unrecognizable. Occasionally, terraces that do not "catch a contour" are shown by the use of hachures (map of Flathead Coal Area, B. C.).

Many of the small streams emptying into the Mississippi show terracing near the mouth, as does Dutch Creek (secs. 17, 18, and 20, T. 12 S., R. 2 W., Jonesboro sheet, Ill.-Mo.), or Establishment Creek (secs. 31, 32, and 33, T. 39 N., R. 8 E., Renault sheet, Ill.-Mo.).

In Idaho, Washington, and adjacent parts of Canada occur some of the largest alluvial terraces on the continent. One of

these, 300 feet high, at the mouth of Moses Coulee (Malaga sheet, Wash.), could not be distinguished from a rock terrace (pp. 100 and 118) on the topographic map. The lower level along Boise River (Mountain Home sheet, Idaho) may quite possibly be alluvial, though the upper one is more probably rock, as alluvial terraces of that height and breadth are hardly to be expected. Furthermore, one so high would be likely to be more dissected than Smith Prairie, especially along the outer edge.

The terraces shown on the Colorado River in the north part of the Diamond Creek (Ariz.) sheet are all rock, though the only evidence on the map to that effect is their great height, and possibly their continuity, which is greater than would ordinarily be found in alluvial terraces. In fact, rock terraces of slight elevation can be distinguished from alluvial terraces with great difficulty, if at all, on contour maps, except possibly for the greater continuity of the former as compared with the latter.

A slightly different type of terrace, very common in the western states, consists essentially of alluvial fan slopes, rather sharply truncated by the stream occupying the main valley. This is well illustrated on the west side of Salinas River (Soledad sheet, Cal.), particularly near Soberanes School (SW. cor. N. cent. rect.). Very similar is probably the terrace on the north side of Colorado River (Yuma sheet, Cal.-Ariz.), near Maggies Well. Such a feature as the bench on the northeast side of Cajon Canyon (N. cent. rect., San Bernardino sheet, Cal.), probably largely a truncated fan slope, may grade upstream into the more familiar type.

Alluvial terraces are widely distributed throughout the United States, but are more abundant in and adjacent to the glaciated regions.

Additional sheets showing alluvial terraces

Muscle Shoals, Ala. (sec. 30, T. 2 S., R. 11 W.).
Needles special, Ariz.-Cal. (N. cent. part of map).
Priest Valley, Cal. (W. side Salinas River).
Winton, Cal. (Merced River).
Hartford, Conn. (South Windsor).

Rocky Ford, Ga. (cent. N. cent. rect.).
Hennepin, Ill. (at Hennepin).
Lacon, Ill. (at Henry).
Peoria, Ill. (at Peoria).
Kosmosdale, Ky.-Ind. (W. side river).
Minneapolis, Minn. (SW. rect.).
Fonda, N. Y. (S. ½ NE. rect. and N. ½ E. cent. rect.).
Hoosick, N. Y.-Vt. (S. of Hoosick, E. cent. rect.).
Schenectady, N. Y. (north of Vischer Ferry, SE. rect.).
Athalia, Ohio-W. Va. (Crown City, E. cent. rect.).
Caldwell, Ohio (N. of Upper Lowell, SE. rect.).
Parkersburg, Ohio-W. Va. (at Rockland, S. cent. rect.).
Boring, Ore. (Clackamas River).
Portland, Ore. (Asylum, sec. 25, T. 2 N., R. 1 E.).
Beaver, Pa. (Shippingport, W. cent. rect.).
Newcastle, Pa. (opposite West Pittsburgh, N. cent. rect.).
Sewickley, Pa. (Aliquippa Park, W. cent. rect.).
Bamberg, S. C. (cent. E. cent. rect.).
Beaver Creek, Tex. (SE. rect.).
Ketchum, Tex. (cent. N. cent. rect.).
Chelan, Wash. (E. side Columbia River).
Belleville, W. Va.-Ohio (Reedsville, W. cent. rect.).

Flood-plain Features.—

Maps

Upper Chitina Valley, Alaska.	Coahoma, Miss.
Needles special, Ariz.-Cal.	Natchez, Miss.-La.
Princeton, Cal.	Kimmswick, Mo.-Ill.
Vorden, Cal.	Gothenburg, Neb.
Henderson, Ky.-Ind.	Winton, N. C.
Uniontown, Ky.-Ind.	Hillsboro, Ore.-Wash.
Bayou Sara, La.	Portland, Ore.-Wash.
Donaldsonville, La.	Augusta, S. C.-Ga.
West Delta, La.	Barnes Bridge, Tex.

Courtney, Tex.

Although the flood plain of a river is often largely the direct result of lateral planation by the stream, there are a number of associated features that are primarily produced by *alluviation.*

River *bars* are accumulations of *sand* or *gravel* in the river channel. They are usually rather migratory features, and may occupy different positions on two successive editions of the same map. Sand bars are very well shown on the Portland (Ore.-Wash.), the Uniontown (Ky.-Ind.), and the Kimmswick (Mo.-Ill.) sheets.

Where more sediment is being brought to any part of a stream than it can remove, the building of bars becomes excessive, and the stream develops an intricate network of interlacing channels, and is said to be *braided.* Platte River (Gothenburg sheet, Neb.) is a particularly fine example, as are also many of the streams flowing from the ice fronts of Alaskan glaciers (Upper Chitina Valley, Alaska, *U. S. Geol. Survey Bull.* 675, Pl. II.).

Where there is a slight curve in any stream, there is a tendency to cut the outer and silt up the inner side, thus accentuating it until it becomes a *meander.* This is very well shown on the Henderson (Ky.-Ind.) sheet, where the accumulating sand is to be seen at Cypress Bend (W. cent. rect.) and Deadman Island (S. cent. rect.), and the *cut bank* or *meander scarp* opposite these two points.

The large meander on this sheet is cutting itself off, the cut banks (secs. 15 and 20, T. 7 S., R. 11 W.) clearly approaching each other. The cutting-off process has gone still farther on the Natchez (Miss.-La.) sheet (W. cent. rect.), and has been completed at False River (Bayou Sara sheet, La.) producing an *oxbow lake*. The oxbow may, in turn, become nearly dry, as shown on the Coahoma (Miss.) sheet, leaving a distinct *meander scarp*, like that of Dry Bayou (cent. and S. cent. rects.).

Within the large meander on the Henderson (Ky.-Ind.) sheet is a curved "ridge and swale" topography, somewhat resembling beach ridges, that results from the deposition of sand on the inner border of the crescent. The curved ridges northeast of Chowan River (Winton sheet, N. C.) are probably of similar origin. On the Coahoma (Miss.) sheet, some of the low belts are drained and others are true depressions, marked by closed hachured contours. Similar curved depressions are often the actual bed of the partly silted oxbow, in some cases still occupied by the remnants of the lake (NE. ¼ E. cent. rect., Princeton sheet, Cal.). Such alluviation depressions may show on a map with a large interval (Needles special, Ariz.-Cal., interval 50 feet) if they are so placed as to "catch a contour", even though they may be only a few feet deep.

An aggrading stream with a wide flood plain will, in times of flood, drop much of its load at that place where the swift water of the channel comes into contact with the more sluggish backwater, that is, along the edges of its channel, thus building *natural levees*. This process, combined with silting of the river bed, finally raises its level considerably above that of the back swamps. On the Donaldsonville (La.) sheet, the top of the natural levee is about 20 feet above the back swamps. Seepage waters and rainfall form small streams (Bayou Conway and Bayou des Acadiens) which flow away from the river. At one time the Mississippi broke out at Nita Crevass, and built a delta into the swamp, consisting of the low irregular hills marked "Alluvial deposit from Nita Crevass".

Levees occur on the West Delta (La.) sheet (NW. rect.), though not sufficiently high to show by contour. Even so small a stream as New River (Donaldsonville sheet, La.) is built slightly above the main swamp area.

On the Barnes Bridge (Tex.) sheet, the contours on the flood plain turn downstream some distance as a result of the natural levees, then follow upstream between the levees. This is most conspicuous where the 400-foot contour makes loops for Rowlett Creek and Bois d'Arc River (N. cent. rect.). On the Courtney (Tex.) sheet, there is a tendency for small streams to occupy what would in a more humid region be the back swamp area. On the Vorden (Cal.) sheet, the Sacramento River occupies the higher land between back swamp areas at sea level.

Somewhat the same condition obtains along Columbia River (Hillsboro sheet, Ore.-Wash.), resulting in the strip of land between the river and the lake area to the west. On the Augusta (S. C.-Ga.) sheet the least swampy part of the flood plain lies closest to the river.

Other maps showing alluviation features on flood plains

Bars

Cordova, Iowa-Ill.
Leavenworth, Kan.-Mo.
Golconda, Ky.-Ill.
Fremont, Neb.
Nebraska City, Neb.-Iowa-Mo.
Blalock Island, Ore.-Wash.
Troutdale, Ore.-Wash.
Harrisburg, Pa.
New Martinsville, W. Va.-Ohio.

Braided streams

Bridge River, B. C.
Santa Anna, Cal.
Glendive, Mont.-N. D.
Kintla Lakes, Mont.
Lexington, Neb.
Paxton, Neb.
Eugene, Ore.
Upper White River, Yukon Terr.
Wheaton, Yukon Terr.

Meanders

Middletown, Conn.
Mt. Carmel, Ill.-Ind.
Baton Rouge, La.
Frazer, Mont.
Nemaha, Neb.-Mo.
Williamston, N. C.
Conesville, Ohio.
Buckholts, Tex.

Oxbows

Morrilton, Ark.
Chester, Ill.-Mo.
New Haven, Ill.-Ind.-Ky.
Milliken, La.
Holyoke, Mass.-Conn.
Moon Lake, Miss.
Poplar, Mont.
Mission, Tex.

Recent meander scarps

Chico Landing, Cal.
Westley, Cal.
Dundee, Miss.
Hollywood, Miss.
Lake Cormorant, Miss.-Tenn.
Lula, Miss.
La Porte, Tex.

Depressions resulting from alluviation

Westport, Cal.
Mound, La.
Jonestown, Miss.
Gallatin, Mo.
Hinsdale, Mont.
Elk Point, S. D.-Neb.-Iowa
Burnet Bay, Tex.

Natural levees

Courtland, Cal.
Kirkville, Cal.
Vernon, Cal.
Gibson, La.
Hahnville, La.
New Orleans, La.
Howth, Tex.
Rockwell, Tex.

Deltas.—

Maps

Mayport, Fla.	Shell Beach, La.
Bonnet Carre, La.	Spanish Fort, La.
Cat Island, La.	St. Bernard, La.
Chef Menteur, La.	Toulme, La.
East Delta, La.	Atlantic City, N. J.
Rigolets, La.	Ithaca, N. Y.

Snohomish, Wash.

Streams that discharge into bodies of standing water form deposits of gravel, sand, or silt, known as *deltas*. The creek emptying into the south end of Cayuga Lake (Ithaca sheet, N. Y.) is building a delta plain. Duwamish River is building a similar deposit into Elliot Bay (Snohomish sheet, Wash.).

The only very large delta within the area of the United States is that of the Mississippi River. The best single map to show its character is the East Delta (La.) sheet. The narrow strips of swamp land that border the various passes may be looked upon as continuations of the natural levee (p. 76), building forward into the gulf. Whenever a break occurs in this natural embankment, the waters of the river seek the gulf by a new channel, thus establishing *distributaries*. The growth of the resulting delta fingers may finally enclose bodies of water, such as Jackass Bay (cent. rect.). The growth of delta fingers back against the mainland in somewhat similar fashion has been responsible for the formation of Lake Borgne (St. Bernard, Rigolets, Toulme, Shell Beach, and Chef Menteur sheets, La.) and Lake Pontchartrain (Bonnet Carre, Spanish Fort, and Chef Menteur sheets, La.).

As already explained (p. 51), this delta constitutes a neutral shore line that has shallow offshore conditions approximating those of emergence combined with an irregularity of delta fingers that simulates a drowned coast. Offshore bars (Robinson Reef, East Delta sheet, La.) and spits (Cat Island sheet, La.) show the nature of the modification that waves are producing. The smooth curve along the west side of Lake Pontchartrain (Bonnet

Carre sheet, La.) probably represents the mature stage of a once much less regular shore line.

Mud lumps (East Delta sheet, La.), a type of offshore island characteristic of the Mississippi delta (p. 51), are subject to rapid removal by wave attack.

Tidal deltas produced by tidal currents through the inlets of offshore bars (Atlantic City sheet, N. J.) have already been described (p. 49).

Submerged deltas occur in many areas, but can be seen only on those sheets on which offshore contours are printed. Such a delta is present opposite the mouth of St. Johns River (Mayport sheet, Fla.), the submerged ridges on either side of the river mouth closely resembling natural levees.

Other maps showing deltas

Frazer River Delta, B. C.
Antioch, Cal.
Karquines, Cal.
Santa Anna, Cal.
Montpelier, Idaho-Wyo.-Utah.
Bodreau, La.
Dime, La.
Fort Livingston, La.
Forts, La.
Quarantine, La.
West Delta, La.
Calumet special, Mich.
Chautauqua, N. Y.
Skaneateles, N. Y.
Chiwaukum, Wash.
Mt. Vernon, Wash.
Samish Lake, Wash.

Submerged deltas

Fernandina, Fla.
Cumberland Island, Ga.
Wadmelaw Island, S. C.

Erosion by Running Water

A very large proportion of our familiar topography is carved by running water. It is to topography of this origin that we look almost entirely for our interpretation of structure; hence the work of running water in land sculpture will be given more space than that of any other physiographic agent.

A region emerging from the sea to any considerable height will be dissected, and will ultimately be reduced again to a featureless plain, or *peneplain*, at or near sea level. Since this

erosion history begins and ends with a plain, it is spoken of as an *erosion cycle.*

The Erosion Cycle—Its Stages.—In different parts of the cycle a region will have notably different characteristics, and in order to describe specifically these portions of the cycle physiographers have adopted three terms: *youth*, *maturity*, and *old age*. If two regions, one of weak rocks and another of resistant, be raised at the same time to the same elevation under identical climatic conditions, the one with the easily eroded rocks may be reduced to a featureless plain before erosion has well started on the more resistant area. It is obvious, therefore, that the *stages* of the cycle, *youth*, *maturity*, and *old age*, mark the amount of *work* accomplished by erosion on the area, and are in no sense a measure of absolute time elapsed. The region of less resistant rocks has passed through its cycle to old age in the same length of time that has permitted the more resistant rock area to reach only late youth or early maturity. Following the human analogy, the one has aged more rapidly than the other.

It follows, then, that a single stream may age more or less rapidly than the region as a whole, and we must understand definitely whether reference is being made to a single feature or to the entire area. Furthermore—and herein has arisen much confusion—we must develop two sets of criteria, one for the stages in the cycle of a region, another for the stages in the cycle of a single valley.

Criteria for the Erosion Stages of a Single Valley.—

Maps

Mt. Trumbull, Ariz.
Yosemite, Cal.
Talking Rock, Ga.
Priest Lake, Idaho-Mont.
Chester, Ill.-Mo.
Galena, Ill.-Iowa.
La Salle, Ill.
St. Louis, east sheet, Ill.-Mo.
Patoka, Ind.-Ill.
Mound, La.
Pawpaw, Md.-W. Va.-Pa.
Aitkin, Minn.
Vicksburg, Miss.-La.
Craig, Mo.-Neb.
Crystal City, Mo.-Ill.
St. Louis, east sheet, Mo.-Ill.
Chelsea, Mont.
Havre, Mont.
Lexington, Neb.
Wheeling, W. Va.-Ohio-Pa.
Mauston, Wis.

While a stream is considerably above its immediate *base level*, it actively deepens its channel. Widening is going on at the same time, but less rapidly, so that a deep, narrow valley results. The low places in the stream course, where the velocity of the current is checked, are built up by deposition of the material eroded from the higher parts, until a smooth curve is produced, down which the stream is just able to move its load of sediment, without either cutting or filling. When that condition is reached, the stream is said to be *graded*, or *at grade;* that is, it has attained its *profile of equilibrium.*

From this point on, down-cutting practically ceases, or becomes exceedingly slow, whereas lateral cutting, which was going on all the time but which was overshadowed in importance by the rapid deepening of the valley, becomes the dominant process, and the stream begins to develop a *flood plain.* This is the most striking single change in the life history of a river, and, since the down-cutting is much more rapid, in general, than the lateral planation, the profile of equilibrium is established rather early in the evolution of the stream. For that reason, this point has been very aptly chosen as the dividing line between youth and maturity.

On the Wheeling (W. Va.-Ohio-Pa.) sheet, Dixon River (cent. rect.) occupies a distinctly young valley. Little Wheeling Creek, into which it flows, is also young above the mouth of Dixon River, but below that point, down to its junction with Wheeling Creek, narrow bits of flood plain suggest that it has about attained grade, and is, therefore, approximately on the boundary line between late youth and early maturity. Wheeling Creek itself is but little past the dividing line, and, since there are but the merest fringes of flood plain along the Ohio, it is advanced to approximately the same stage.

In a region of much lower relief (La Salle sheet, Ill.) the Vermilion River seems to be at about the same stage, as attested by bits of flood-plain fringe, whereas the Illinois River has advanced into early maturity, with a well-developed flood plain. In a region of enormously greater relief (Mt. Trumbull sheet, Ariz.)

Colorado River valley, which is many times as wide at the brink, does not show a trace of flood plain, and must still be classed as youthful. Even though the Colorado has excavated hundreds of times as great a volume of material as the Illinois, it is not so far advanced in the cycle, because it has accomplished a smaller proportion of the work it has to do.

There do not seem to be any marked episodes between the beginning of a valley and the establishment of the profile of equilibrium which would justify subdivisions of youth, and therefore the terms early, middle, and late youth, as applied to a valley, are necessarily very indefinite; in fact, it does not seem feasible even to attempt to delimit or define them.

A stream at grade, with its velocity much less than in its earlier history, tends to be easily deflected by obstacles, and swings from side to side of its valley, gradually developing *meanders* (p. 75). If the valley is sufficiently wide to allow absolutely free meandering, a stream of a given size will develop meander curves always of approximately a certain width. If, now, on each side of a stream, a tangent to these meander curves be drawn or visualized, the strip of land between may be called the *meander belt.*

Early in the development of meanders, the curves impinge on both walls of the valley, but finally there comes a time when the flood plain is as wide as the normal meander belt for that particular size of stream. This, next after the development of the profile of equilibrium, would seem to be the most distinctive step in the life history of the river, and should undoubtedly serve as another marker between stages. Since nothing that comes after this is as natural a dividing place, it might at first sight seem that this would be the logical point to draw the boundary between maturity and old age. Careful thought should suggest, however, that this is still far earlier than the ultimate stage in the history of the average river, and that to place the boundary between maturity and old age at this point would limit maturity to too brief an episode in the cycle, and throw too large a part of the history into the category of old age.

Because the widening of the valley goes on at a slower and slower rate as it progresses farther and farther in the cycle, so that the later part will be enormously longer under almost any division that can be worked out than the earlier, it seems best to make the dividing line between early and middle maturity the time when the flood plain becomes as wide as a normal meander belt for a stream of the given size.

The Missouri, on the Chelsea (Mont.) sheet, may, therefore. be said to be just passing from early to middle maturity. Milk River, on the Havre (Mont.) sheet, also appears to be about at this transition. Since it is a much smaller stream than the Missouri, its normal meander belt is narrower, and it, therefore, passes from early to middle maturity with a much narrower flood plain. On the other hand, the Mississippi, on the Chester (Ill.-Mo.) sheet, with a much wider flood plain, has only just reached the same stage, because, being a larger stream, its meander belt is wider.

Mississippi River on the Galena (Ill.-Iowa.) sheet is still in early maturity, since its valley is much too narrow to admit of free meander curves appropriate to the size of the river. The same stream, many miles nearer its source (Aitkin sheet, Minn.) has a flood plain several times as wide as its meander belt, and has passed well into or beyond middle maturity, largely because it is working on unconsolidated glacial deposits, which it can erode more easily.

From this stage on, there do not seem to be any distinctive transition points, and the further divisions of the cycle are, therefore, much more arbitrary, and less likely to meet general agreement. It has been suggested that the boundary between middle and late maturity be placed at that stage when the flood plain is from four to five times the width of the meander belt, and the one between late maturity and old age from eight to ten times. These are purely arbitrary limits, but with the lack of natural ones may serve as well as any others, with this exception. Where streams of some size are closely spaced, the intervening divides may be completely cut away before the old-age width is reached. When the divides are entirely cut away, the streams should

probably be considered as in old age, even though the arbitrary limit mentioned above has not been reached.

According to the above classification, the Wabash on the Patoka sheet (Ind.-Ill.) is well into middle maturity, as are also the Missouri River on the Craig sheet (Mo.-Neb.) and the Mississippi on the St. Louis east sheet (Ill.-Mo.). The Mississippi on the Vicksburg (Miss.-La.) and Mound (La.) quadrangles cannot be properly evaluated, since only one side of the flood plain is mapped, but is probably late mature.

The flood plain of the Lemonweir River (Mauston sheet, Wis.), if it be considered to include half the area between it and Yellow River, is at least twenty times as wide as its normal meander belt, and may be fairly said to represent typical old age, though its actual width in miles is no greater than that of the Mississippi at St. Louis (St. Louis, east sheet, Ill.-Mo.), which is only in middle maturity.

If a river does not meander (Crystal City sheet, Mo.-Ill.), more difficulty is encountered in placing it in the cycle. It can best be classified by comparing it with some other stream of similar magnitude, along which meanders are present, or with some other part of the same stream. Comparison of the Crystal City with the Chester (Ill.-Mo.) sheet will show that the flood plain near Crystal City is just about wide enough to accommodate an appropriate meander.

In case of a braided stream like the Platte (Lexington sheet, Neb.), it is very difficult to decide what would constitute an appropriate width of meander belt. Ordinarily, it is from eight to twenty times the actual width of the stream. The real width of a stream like the Platte, however, is hard to estimate, but, if it be taken as the average width from outside to outside channel, the flood plain is about twenty times as wide, or, clearly, more than a normal meander belt. It would seem safe, therefore, to say that the Platte, on this sheet, is at least in middle maturity.

It has already been suggested (p. 84) that one part of a stream may be in a different stage than an adjacent section. This is admirably shown on the Priest Lake (Idaho-Mont.) sheet,

Kootenai Valley being young at the east border of the map, and middle mature at the north border, probably owing to difference in the resistance of the rock. The same situation occurs on Coosawattee River (Talking Rock sheet, Ga.). Local conditions of excessive hardness may result in youthful falls or rapids in a valley that is otherwise well matured. Widening of the Yosemite and Hetch Hetchy valleys (Yosemite sheet, Cal.) is probably the result of glaciation rather than differential hardness. These valleys are distinctly youthful, except for a short stretch in each that is somewhat more matured.

Before closing this discussion, a word of caution should be sounded. There is a marked tendency among students of the subject, and even among teachers, to consider that any stream with well-developed meanders is in old age. This tendency should be discouraged, because it would make of maturity only a brief episode in the life history of a river, and prolong old age unduly for a well-balanced division of the cycle (pp. 81–84).

Another word of caution should be added. Intrenched meanders (pp. 119–121), inherited from a previous cycle of erosion, are no measure of the stage of the present erosion history. The Potomac River on the Pawpaw (Md.-W. Va.-Pa.) sheet has a clearly defined meander belt, but is only in very early maturity of the present cycle.

Additional maps illustrating the stages in the cycle of a single valley

Youth

Bright Angel, Ariz. (Colorado River).
Verde, Ariz. (Deadmans Canyon).
Big Trees, Cal. (Stanislaus River).
Copperopolis, Cal. (Stanislaus River).
Rico, Colo. (Dolores River).
Bisuka, Idaho (Snake River).
Lolo, Idaho-Mont. (Lochsa River).
Mountain Home, Idaho (Boise River).
London, Ky. (Rock Castle River).
Bucksport, Maine (Penobscot River).
Antietam, Md.-Va. (Potomac River).
Ellicot, Md. (Patapsco River).
Becket, Mass. (Westfield River).
Fayetteville, W. Va. (New River).
Witbeck, Mich. (Michigamme River).

Boundary, youth—early maturity

Cornwall, Conn.-N. Y. (Housatonic River).
Waterbury, Conn. (Naugatuck River).
Dahlonega special, Ga. (Chestatee River).
Danville, Ill.-Ind. (Vermilion River).
Lehigh, Iowa (Des Moines River).
Hays, Kan. (Smoky Hill River).
Pikeville, Ky. (Shelby Creek).
Chesterfield, Mass. (Westfield River).
Lowell, Mich. (Thornapple River).
Forsyth, Mo. (White River).
Sidney, Ohio (Miami River).
Beckley, W. Va. (New River).
Milton, W. Va. (Guyandot River).
Wallula, Wash. (Snake River).

Early maturity

Bakersfield special, Cal. (Kern River).
Elcajon, Cal. (San Diego River).
San Benito, Cal. (San Benito River).
Platte Canyon, Colo. (South Platte River).
Cataldo, Idaho-Mont. (Coeur d'-Alene River).
Elizabeth, Ill. (Apple River).
Renault, Ill.-Mo. (Establishment Creek).
Tallula, Ill. (Sangamon River).
Elkader, Iowa-Wis. (Mississippi River).
Dodge, Kan. (Arkansas River).
Harold, Ky. (Levisa Fork).
Seneca, Md.-Va. (Potomac River).
Iuka, Miss.-Ala.-Tenn. (Tennessee River).
Owego, N. Y. (Susquehanna River).
Chesterhill, Ohio (Hocking River).
Beaver, Pa. (Raccoon Creek).

Boundary, early—middle maturity

Clearwater River and Foghorn Creek, B. C.
Lanes Bridge, Cal. (San Joaquin River).
Monterey, Cal. (Carmel River).
Weiser, Idaho-Ore. (Snake River).
Baldwin, Ill. (Kaskaskia River).
Renault, Ill.-Mo. (Mississippi River).
Concordia, Kan. (Republican River).
Kansas City, Kan.-Mo. (Missouri River).
Dunmore, Ky. (Green River).
Ionia, Mich. (Grand River).
Assinniboine, Mont. (Milk River).
Ray, N. D. (Missouri River).
Newcomerstown, Ohio (Tuscarawas River).
Urichsville, Ohio (Tuscarawa River).
Olivet, S. D. (James River).
Pysht, Wash. (Soleduck River).

Middle maturity

Nepesta, Colo. (Arkansas River).
Princeton, Ind.-Ill. (White River).
Des Moines, Iowa (Des Moines River).
Salina, Kan. (Saline River).
Nortonville, Ky. (Pond River).
Knobnoster, Mo. (Blackwater River).
Neosho, Mo. (Shoal Creek).
Iuka, Miss.-Ala.-Tenn. (Bear River).
Nashua, Mont. (Milk River).
Wolf Point, Mont. (Missouri River).
Humboldt, Neb. (Nemaha River).
Waverley, Ohio (Scioto River).
Elk Point, S. D.-Neb.-Iowa. (Big Sioux River).
Sultan, Wash. (Snoqualmie River).

Boundary, middle—late maturity

Carlyle, Ill. (Kaskaskia River).
Equality, Ill. (Saline River).
Wilmington, Ill. (Kankakee River).
Vincennes, Ind.-Ill. (Wabash River).
Queen City, Mo. (Chariton River).
Bowdoin, Mont. (Beaver Creek).
Harlem, Mont. (Milk River).
Saco, Mont. (Beaver Creek).
Williamston, N. C. (Roanoke River).
Peeples, S. C.-Ga. (Savannah River).
St. George, S. C. (Edisto River).
Shirley, S. C.-Ga. (Savannah River).
Navasota, Tex. (Brazos River).
Texarkana, Tex.-Ark. (Sulphur River).
Broadhead, Wis. (Sugar River).

Late maturity—old age

Denzer, Wis. (Honey Creek).

Different stages on same stream

Friant, Cal. (San Joaquin River).
Axial, Colo. (Yampa River).
Farmington, Conn. (Connecticut River).
Cordova, Iowa-Ill. (Mississippi River).
Buckfield, Maine (Androscoggin River).
Accident, Md.-W. Va.-Pa. (Youghiogheny River).
Holyoke, Mass.-Conn. (Connecticut River).
Fremont, Neb. (Platte River).
Roxabell, Ohio (Paint Creek).
Salem, Ore. (Willamette River).
Elkins, W. Va. (Tygart River).
Denzer, Wis. (Baraboo River).

Criteria for the Erosion Stages of a Region.—

Maps

Bright Angel, Ariz.	Boothbay, Maine.
Flagstaff, Ariz.	Holyoke, Mass.-Conn.
Cucamonga, Cal.	Vergas, Minn.
Williston, Fla.	Chief Mountain, Mont.
Moniac, Ga.-Fla.	Hamilton, Mont.-Idaho.
Waipio, Hawaii.	Gothenburg, Neb.
Bisuka, Idaho.	Winnepesaukee, N. H.
Equality, Ill.	Elmira, N. Y.-Pa.
Highwood, Ill.	Kaaterskill, N. Y.
Jonesboro, Ill.-Mo.	Oberlin, Ohio.
New Haven, Ill.-Ind.-Ky.	Newcomerstown, Ohio.
Springfield, Ill.	Chicora, S. C.
Cordova, Iowa-Ill.	Shirley, S. C.-Ga.
Lehigh, Iowa.	Elk Point, S. D.-Neb.-Iowa.
Milo, Iowa.	Pikeville sheet, Tenn.
Madisonville, Ky.	Pikeville special quadrangle, Tenn.
Nortonville, Ky.	Wartburg, Tenn.
Bayou Sara, La.	Wellington, Utah.
New Orleans, La.	Matthews, Va.

Cameron, W. Va.-Pa.-Ohio.

Under ordinary climatic conditions, when a region is uplifted, steams begin to dissect it. Along their sides tributaries form, and these, in turn, develop tributaries until, finally, the region is completely dissected, so that none of the original upland remains. The main rivers may reach grade, and start to develop flood plains, before all of the upland is cut away, but the smaller streams continue to deepen their valleys. During this earlier part of the cycle, the region, in general, is becoming more and more rugged, and the local relief greater.

After the larger proportion of the streams have reached grade, and ceased deepening, the divides continue to become narrower and lower, until only gentle swells remain between adjacent drainage ways, and, finally, the watersheds may be wholly planed away. This completes the cycle, and such a region worn down to *base level* is said to be a *peneplain.* For convenience in description, as well as to clarify our ideas as to the exact details

of this planation process, we divide the cycle into stages, commonly designated *youth*, *maturity*, and *old age*.

The most conspicuous single transition in the erosion history of any region is the point at which the last remnants of the original upland disappear. Since this occurs fairly early in the cycle, it has very aptly been chosen to mark the division between youth and maturity.

Extreme youth, with no large valleys, but with many small gullies that will finally gnaw back headward and drain the upland plain, is well illustrated on the Highwood (Ill.) sheet. The Lehigh (Iowa) sheet affords an excellent example of a region in typical youth. The main valley, it is true, has about attained its profile of equilibrium, and has developed here and there a narrow fringe of flood plain. The valley, therefore, is about on the borderland between late youth and early maturity (p. 82). Most of the upland, nevertheless, is quite untouched, and the original plain is the dominating feature of the region, which is, consequently, but little advanced in its history, and may reasonably be classed as in early youth.

Compared with the Lehigh sheet, the Springfield (Ill.) quadrangle shows much smaller remnants of undissected upland and is clearly more advanced in the cycle, though still not past middle youth. Its main stream, however, is about on the boundary between early and middle maturity (p. 83).

Somewhat later yet in the cycle is the southeast half of the Milo (Iowa) sheet, in which there are still considerable remnants of the original upland, but much smaller and more ragged in outline. This sheet does not appear to be as sharply dissected as the two preceding it, because of the use of the 20- instead of the 10-foot interval. Were it mapped with the smaller interval, the unscarred upland remnants would be more exactly delimited, and would appear somewhat smaller. The southeast half of the Milo sheet is properly spoken of as in late youth, and the northwest half has youthful uplands, though Des Moines River is entering middle maturity, and South River is fully mature (p. 84).

On the Cameron (W. Va.-Pa.-Ohio) quadrangle there are no undissected remnants of the upland, the many tributaries having worked headward until they have completely cut up the original surface. On this sheet there are no broad valley bottoms, almost the entire area being hillside. It is in typical early maturity.

From this stage onward, the larger valleys deepen very slowly, and gradually broaden; the smaller valleys continue to deepen; and divides slowly become lower, until lowland dominates and divides become almost imperceptible. In this part of the history of a region, there does not appear to be any definite and clear-cut change which may serve as a satisfactory dividing line between maturity and old age. Certainly, no area can properly be classed in the latter category while any considerable part of the original upland remains, nor until 50 per cent or more of its area has been reduced approximately to flood-plain level.

On the Newcomerstown (Ohio) sheet, many of the smaller valleys have well-developed flood plains, and the main river is just passing into middle maturity; little or no flat-topped upland is left. The sheet is distinctly more advanced than the Cameron quadrangle.

The Equality (Ill.) sheet is also considerably more advanced than the Cameron, in spite of the fact that small bits of the upland still persist. Dissection has not been uniform, the north part of the area being widely reduced to flood-plain level, so that it might, considered by itself, be called late mature, though the south part is still in early maturity.

On the Nortonville (Ky.) sheet, in spite of the fact that small bits of flat-topped upland still remain, the total degree of dissection is greater than in the Newcomerstown area, and may surely be said to have reached middle maturity.

In the Madisonville (Ky.) region, a few small upland areas occur, which may doubtfully represent the original plain, or something near it. A large part of the region has been reduced essentially to river level, and the divides are distinctly fragmentary. The area is not earlier than late mature.

A still larger proportion is reduced to lowland on the New Haven (Ill.-Ind.-Ky.) quadrangle, which probably comes as near to old age as any map available. Since the reduction of the last remnants is an extremely slow process, the cycle is usually interrupted before perfect old age is reached, and typical illustrations are rare.

From the foregoing discussion and illustrations, it will be evident that occasional remnants of the original upland may persist in a region otherwise maturely dissected; or that a mature river may cross a region the dominant features of which are youthful; so that, although the main incident in the boundary between youth and maturity is the extinction of the original upland, other conditions must be taken into consideration. Mature features may occur in a young region, or youthful features in a mature region, and care must be taken to weigh these properly, in any attempt to classify a region in the erosion cycle.

This fact is strikingly exhibited on the Cordova (Iowa-Ill.) sheet, at least one-third of which is reduced nearly to flood-plain level, even though flat upland persists at some points. Small areas, if viewed alone, are in late youth, or certainly not past early maturity, though we are surely justified in placing the region as a whole in or near middle maturity. The same contrast is to be noted on the Gothenburg (Neb.) sheet, the northeast portion of which has been very completely reduced to a plain typical of old age. South of the river and immediately adjacent to the flood-plain scarp, the dissection is early mature, but in T. 9 N., R. 24 W., and elsewhere on the map, is sufficient flat upland to justify the term late youth. The contrast is so great that no single term will do justice to the description, and the different parts of the area must be classified separately.

A somewhat common situation, but one which greatly complicates the problem, is exemplified on the Elk Point (S. D.-Neb.-Iowa) sheet. The original valley of the Missouri River, including the present area of the terrace at Vermilion (W. cent. rect.), is from four to seven times as wide as the normal meander belt, and is, therefore, definitely in middle maturity.

The valley crosses a region otherwise not past early maturity. The Missouri and Vermilion rivers have built and later entrenched themselves in a terrace (p. 71), the major part of which is still undissected original upland (terrace) surface in early youth. Its relation to the higher and more dissected upland is termed *topographic unconformity*. No adequate description of the stages in this region can omit to mention separately the higher upland dissected to early maturity, the youthful terrace, and the fully mature valleys of the Missouri, Vermilion, and Big Sioux rivers.

Somewhat comparable is the marked topographic unconformity on the Matthews (Va.) sheet between the very youthful marine terrace at 15 to 20 feet and the much more dissected upland plain at 70 to 80 feet, now about in middle youth. No classification of the stages on this and adjacent sheets would be complete without separate mention of these contrasting features. Simply to say that the region is in youth is wholly inadequate.

Closely analogous is the contrast (Cucamonga sheet, Cal.) between the early mature dissection of San Antonio Mountains, and the almost entirely uneroded piedmont alluvial plain to the south. There is some doubt as to the propriety of attempting to assign a plain like this to the erosion cycle. Since it is a plain of deposition on which erosion has as yet done almost nothing, it must, if classified at all, be placed at the very beginning of youth. The above sheet affords another example of topographic unconformity.

A similar piedmont alluvial plain south of Book Cliffs (Wellington sheet, Utah) has been notably dissected, perhaps about to middle youth.

Like a piedmont alluvial plain, the surface of a delta, such as that shown on the New Orleans (La.) sheet, must, if classed in the cycle at all, be placed at the very beginning of youth. On the other hand, the Bayou Sara (La.) sheet gives conclusive evidence of the reduction of the flood plain from a once higher level, so that it is actually well along in a very definite erosion history.

The character of the topography during the earlier stages of the cycle is largely dependent on the nature of the surface on which the new drainage starts; and this, in turn, on the geologic process or processes that built the plain. For example, the Shirley (S. C.-Ga.) sheet is very characteristic of extreme youth on a recently emerged coastal plain, as are also the Moniac (Ga.-Fla.) and Chicora (S. C.) sheets, with their high-level swamps still undrained, probably held back by beach ridges (p. 46). A rather unusual type of coastal-plain youth is shown on the Williston (Fla.) sheet, the remarkable lack of surface streams being doubtless related to solution and underground flow in limestone.

Characteristic of youth on the recently exposed plains of the glacial Great Lakes is the Oberlin (Ohio) sheet. Here, the slope of the subaqueous plain that later became land was apparently somewhat steeper, and beach ridges less conspicuous, so that the area resulting from emergence was probably less swampy even in its initial stages. The streams across the area are doubtless *extended*, that is, existed before the plain emerged from the lake, and "extended" themselves as the lake level fell and the land was uncovered.

Youth on a surface built exclusively of morainal deposits (Vergas sheet, Minn.) may, even in its initial stages, be distinctly rugged, and is usually marked by excessive lake areas. Where glaciation has less completely obscured the old preglacial topography (Winnepesaukee sheet, N. H.), the earlier mature dissection may be strikingly in evidence, with youthful swamps and lakes superimposed upon it. In some cases (Holyoke sheet, Mass.-Conn.) the earlier mature dissection is the dominant feature, and the glacially superimposed youth distinctly subordinate.

Mountain topography in late youth or early maturity, on which have been superimposed youthful lakes and falls resulting from glaciation, is well shown on the Hamilton (Mont.-Idaho) and Chief Mountain (Mont.) sheets, the glacial modification being much more extreme on the latter than on the former.

Merely to describe any one of the above areas as youthful, without mention of its origin, would give no discriminating picture. To describe one as a youthful morainal area, another as a recently emerged coastal plain, and another as a mountain area dissected to early maturity and recently glaciated, makes the picture much more definite. These distinctions, based on the origin of the plain, disappear more or less rapidly as the cycle progresses, but are of great importance in the youthful stage.

A given region is more rugged in early maturity than in either earlier or later stages, but its absolute local relief is dependent on altitude above its immediate base level. Clearly, a region, no part of which is more than 100 feet above sea level (Matthews sheet, Va.), can never be very rugged in any stage of its history, whereas a region like the Colorado Plateau (Bright Angel sheet, Ariz.) may still be in early to middle youth, and have canyons 4,000 to 6,000 feet deep. To our description should be added, then, a statement as to whether the relief is slight, medium, or great, or it should be stated specifically, to carry the most perfect picture of a region.

The larger the scale and the smaller the contour interval the more accurately can the erosion stage of a region be judged from the map. On the Wartburg (Tenn.) sheet much apparently flat-topped upland would normally lead to the classification of the topography as in late youth. With the use of a smaller interval, however, increased detail might show these uplands to be considerably scarred by erosion, and place the sheet in early maturity.

The influence of scale and interval in interpreting the stage of the cycle is strikingly brought out by contrasting the Pikeville (Tenn.) sheet (scale $\frac{1}{125,000}$ and 100-foot interval) with the Pikeville special quadrangle (scale $\frac{1}{62,500}$ and 20-foot interval). Walden Ridge on the older map seems to be composed of considerable areas of flat upland. The newer large-scale map makes it obvious that this upland is itself rather maturely dissected by a system of shallow valleys, contrasting strongly with the canyon of Richland Creek. Whether this shallow mature network on the upland has been controlled by a temporary base level on

harder horizontal rock, or was produced in a previous cycle which has been interrupted by uplift, does not concern us especially in this particular discussion. The chief point to be made clear is that, in spite of the shallow, mature dissection, Walden Ridge is a flat upland, almost unscarred by the deeper erosion now working back into it along Richland Creek and Sequatchie Valley. It is, therefore, in early youth of its present cycle.

The shallow dissection of the upland plain on the Bisuka (Idaho) sheet, though rather mature in itself, bears exactly the same relation to the canyon of Snake River, with respect to which the region is in early youth. The upland on the Kaaterskill (N. Y.) sheet, though maturely dissected, is youthful with respect to dissection by Kaaterskill and Plaatkill creeks. On the Waipio (Hawaii) sheet, the upland is somewhat maturely dissected by a closely spaced set of small streams, presumably the initial consequent drainage lines down the volcanic slope, but is in early youth with respect to dissection by the striking canyons on the north coast.

A condition like that on the Flagstaff (Ariz.) sheet may be somewhat misleading. The broad areas, such as Kendrick Park (N. cent. rect.), that appear somewhat like mature valleys, are, in reality, simply portions of the upland plain on which volcanic cones have been built. The only dissection of the upland occurs in the canyons at the south edge of the sheet, and the area is in early youth.

Another somewhat abnormal situation occurs on the Boothbay (Maine) sheet. This region was dissected to early or middle maturity; was glaciated, with the superimposition of certain youthful features, such as lakes and swamps; and was then drowned. The coast line is in early youth (p. 43).

In the mature stage of the cycle, which is characterized by the maximum number of valleys per unit area, different regions exhibit great differences in the minuteness of dissection. This is referred to as the *texture* of the topography. A very *fine-textured* topography occurs on the Jonesboro (Ill.-Mo.) sheet, and a notably *coarse-textured* one on the Elmira (N. Y.-Pa.)

sheet. Both are on sedimentary rocks, and both sheets are mapped with the same scale ($\frac{1}{62{,}500}$) and the same interval (20 feet).

Additional maps illustrating the stages of the erosion cycle of a region

Pre-erosion stage

Anaheim, Cal.
Cache Slough, Cal.
Jersey, Cal.
Karquines, Cal.
San Bernardino, Cal.
Bonnet Carre, La.
Cheniere Caminada, La.
Point of Sands, N. M.
Tularosa, N. M.
El Paso, Tex.

Extreme youth on coastal plains

Cambon, Fla.
Lawtey, Fla.
Tsala Apopka, Fla.
Everett City, Ga.
Folkston, Ga.-Fla.
Nanticoke, Md.
Edenton, N. C.
Green Pond, S. C.
Wadmelaw Island, S. C.
Hampton, Va.

Extreme youth on lake plains

Calumet, Ill.-Ind.
Evanston, Ill.
Detroit, Mich.
Romulus, Mich.
Wyandotte, Mich.
Ridgeway, N. Y.
Casselton, N. D.
Fargo, N. D.
Maumee Bay, Ohio-Mich.
Perry, Ohio.

Extreme youth on glacial deposits

Grays Lake, Ill.-Wis.
Lansing, Mich.
Mason, Mich.
Battle Lake, Minn.
Deerwood, Minn.
White Bear, Minn.
Clyde, N. Y.
Palmyra, N. Y.
Neshkoro, Wis.
Portage, Wis.
Sun Prairie, Wis.
Waukesha, Wis.

Early youth, beyond initial stage

Mountain Home, Idaho.
Marseilles, Ill.
Boone, Iowa.
Waukee, Iowa.
Ionia, Mich.
Minneapolis, Minn.
Kremlin, Mont.
Ray, N. D.
Sidney, Ohio.
Crater Lake National Park, Ore.
Watrous, N. M.
Peever, S. D.-Minn.
Quincy, Wash.

Middle youth

Kaibab, Ariz.
Ortigalita, Cal.
Soda Canyon, Colo.
Colchester, Ill.
Monmouth, Ill.
Mt. Olive, Ill.
Siloam Springs, Okla-Ark.
Todd Lakes, Mont.
Tule Valley, Mont.
Santa Clara, N. M.
Higginsport, Ohio.
Indian Wells, Tex.
Escalante, Utah.
La Sal, Utah.
Malaga, Wash.
Superior, Wis.-Minn.
Canyon, Yellowstone Park, Wyo.
Gallatin, Wyo.

Late youth

Marshal, Ark.
San Cristobal, Colo.
Winthrop, Iowa.
Russel, Kan.
Smith Center, Kan.
Ellicot, Md.
Macon, Mo.
Neosho, Mo.
Palmyra, Mo.
Huntley, Mont.
Red Cloud, Neb.-Kan.
Lisbon, Ohio.
Huntingdon, Pa.
Wartburg, Tenn.
Heathsville, Va.-Md.
Morattico, Va.
Williamsburg, Va.
Mt. Adams, Wash.
Mt. Aix, Wash.
Ishawooa, Wyo.

Preglacial topography with superimposed youthful features

Mt. Lyell, Cal.
Rocky Mountains National Park, Colo.
Litchfield, Conn.-N. Y.
Bucksport, Maine.
Kezar Falls, Maine-N. H.
Moosehead Lake, Maine.
The Forks, Maine.
Becket, Mass.
Kintla Lakes, Mont.
Indian Lake, N. Y.
Mt. Adams, Wash.
Fremont Peak, Wyo.

Early maturity

Big Trees, Cal.
Waukon, Iowa-Wis.
Buckhorn, Ky.
London, Ky.
Forsyth, Mo.
Lolo, Idaho-Mont.
Athalia, Ohio-W. Va.
Conesville, Ohio.
Sewickley, Pa.
Hurley, Va.-Ky.
Fayetteville, W. Va.

Middle maturity

Dardanelle, Ark.
Magazine Mountain, Ark.
Shawneetown, Ill.-Ky.
New Harmony, Ind.-Ill.
Patoka, Ind.-Ill.
Petersburg, Ind.
Wilton Junction, Iowa.
Calhoun, Ky.
Central City, Ky.
Morganfield, Ky.
Providence, Ky.
Craig, Mo.-Neb.
Navarre, Ohio.
Franklin, Tenn.
Gay Hill, Tex.

Late maturity and old age

Eldorado, Ill.
Mt. Carmel, Ill.-Ind.
Henderson, Ind.-Ky.
Owensburg, Ind.-Ky.
Princeton, Ind.-Ill.
Vincennes, Ind.-Ill.
Newburg, Ky.-Ind.
Sutherland, Ky.
Uniontown, Ky.-Ind.

Areas showing strong contrasts in stage

Bakersfield, Cal.
St. Louis, east sheet, Ill.-Mo.
Aitkin, Minn.
Natchez, Miss.-La.
David City, Neb.
Raton, N. M.-Colo.
Williamston, N. C.
Mentor, Ohio.
Portland, Ore.-Wash.
Hollow Springs, Tenn.
Tappahannock, Va.
Kendall, Wis.

Texture—fine

San Benito, Cal.
Carbondale, Ill.
Harold, Ky.
Whitesville, Ky.
Vicksburg, Miss.-La.
Macon, Mo.
Todd Lakes, Mont.
Walnut Wells, N. M.
Caldwell, Ohio.
Conesville, Ohio.
Heathsville, Va.-Md.
New Martinsville, W. Va.-Ohio.
Kendall, Wis.

Texture—coarse

Elcajon, Cal.
Cornwall, Conn.-N. Y.
North Conway, N. H.-Maine.
Hammondsport, N. Y.
Ithaca, N. Y.
Kaaterskill, N. Y.
Naples, N. Y.
Owego, N. Y.
Tully, N. Y.
Gaines, Pa.
Tioga, Pa.
Trout Run, Pa.
Sumas, Wash.
Denzer, Wis.
Webster Springs, W. Va.

Effect of Rock Hardness—Drainage Patterns.—

Maps

Vandiver, Ala.	Corazon, N. M.
Diamond Creek, Ariz.	Niagara, N. Y.
Mount Trumbull, Ariz.	Niagara Falls, N. Y.
Tusayan, Ariz.	Mt. Mitchell, N. C.-Tenn.
Cucamonga, Cal.	Kiefer, Okla.
Mt. Whitney, Cal.	Delaware Water Gap, Pa.-N. J.
Priest Valley, Cal.	Harrisburg, Pa.
San Mateo, Cal.	Hollidaysburg, Pa.
Spanish Peaks, Colo.	New Bloomfield, Pa.
Waipio, Hawaii.	Briceville, Tenn.
Holyoke, Mass.-Conn.	Uvalde, Tex.
Forsyth, Mo.	Henry Mountains, Utah.
Hamilton, Mont.-Idaho.	King William, Va.

Monterey, Va.-W. Va.

Rocks of unequal hardness, or perhaps it is better to say of unequal resistance to the agents of weathering and erosion, wear down at unequal rates during the cycle, thus giving rise to many familiar topographic forms. The effect of resistant and non-resistant rocks on the topography is dependent on the position, or *attitude*, of the rock masses. With alternating layers, in horizontal position, the soft beds wear back undermining the harder, thus finally producing *rock terraces* on the sides of valleys, as on the Diamond Creek (Ariz.) sheet. Such terraces cannot always be distinguished on the map from those of alluvial origin (p. 71), although great height, combined with exceptional continuity, usually indicates the rock type. Such rock terraces may also be confused with benches produced by partial peneplanation (pp. 116–117), but are likely to be more symmetrical, the uniform structure resulting in about the same width of terrace on both sides of the valley at corresponding levels (Diamond Creek and Mt. Trumbull sheets, Ariz.).

A hard cap may also result in *mesas*, as on the Corazon (N. M.) sheet, or in *falls* of the Niagara type (Niagara Falls quadrangle, N. Y.), or in *regional escarpments* (pp. 135–148), such as that shown on the Niagara (N. Y.) quadrangle, or the Kiefer (Okla.)

sheet. These forms may safely be interpreted as meaning a harder rock overlying a softer, though whether the cap is igneous or sedimentary cannot be determined from the topographic map.

On a recently emerged coastal plain, the slope of which is toward the sea, the initial stream courses are a consequence of the initial slope of the land. The Mattaponi and Pamunkey rivers on the King William (Va.) sheet are typical *consequent* streams. The many small parallel streams on the Waipio (Hawaii) sheet are presumably also initial consequent down the steep slope of a volcano.

Even though the rock beds may be in alternating harder and softer layers, their slope toward the sea is nearly identical with that of the land surface, so that a single formation outcrops over wide areas. The tributary streams, therefore, as they develop encounter no notable differences of hardness, and, if the slope is not too steep, branch in all directions about equally. These tributary streams are said to be *insequent*, that is, not sequent or dependent on any obvious structure. A pattern of drainage so developed is called *dendritic*, because it branches like a fern or tree (King William sheet, Va., and Forsyth sheet, Mo.). Even though the rocks may be folded at high angles, a similar drainage pattern will result (p. 127), if there are no notable differences in hardness to control the direction of the branches (Mt. Mitchell sheet, N. C.-Tenn.). Massive igneous rocks for the same reason (p. 126) have a dendritic drainage pattern (N. ½ Cucamonga sheet, Cal.).

If, on the other hand, the tilted layers are of unequal hardness, and outcrop in narrow parallel belts, the tributaries etch out the softer layers, leaving the harder as the divides. Such tributaries are dependent on the substructure, and are, therefore, termed *subsequent*, and the parallel arrangement of ridges and valleys that results is spoken of as *trellis* or *trellised* drainage (Monterey sheet, Va.-W. Va.). This frequently results in a striking "ridge and valley" topography (Harrisburg sheet, Pa.), or in *elbow* or *zigzag* ridges (Hollidaysburg sheet, Pa.). Sometimes the dipping hard layer may be igneous (Holyoke sheet, Mass.-Conn.),

though this fact cannot be ascertained on the topographic map. The contrast between the trellised and dendritic drainage patterns is strikingly brought out on the Briceville (Tenn.) sheet (see also pp. 126–130).

Many of the streams in such a region break through the ridges in notable *water gaps* or *narrows* (Delaware Water Gap sheet, Pa.-N. J., and New Bloomfield sheet, Pa.). Such water gaps may have been formed in the following manner: At one time the whole area of the New Bloomfield and bordering sheets was a plain, or, better, a peneplain, at about the level of Peters and Cove Mountains, which then stood much lower than now. At such a stage the Juniata and Susquehanna rivers do not seem to have been hindered at all by the hard rocks that form these mountain ranges, either because they were worn so completely to base level that the streams could meander over them freely above the deep soils, or, possibly, because the peneplain had been lowered into the sea, and buried beneath a thin veneer of coastal-plain sediment over which new streams could wander unhindered.

When the region was uplifted (*rejuvenated*) these streams began at once to *intrench* themselves in the peneplain they had formed. They could not, in their upper courses, cut downward any faster than they were able to saw through the obstructing hard rock, but they could wear the soft rocks in wider valleys than the hard, even if they could not cut them deeper. There resulted a narrow place in the valley on the site of each hard layer of rock. Every student of physiography must disabuse himself of the once prevalent idea that the low plains behind the hard-rock ridges were ever the sites of lakes which rose high enough to give outlet over the ridge and start the notch. The wide plain was cut down *pari passu* with the narrower notch.

Nor must the student get the rather prevalent idea that these rock ridges were raised, of themselves, across the course of the stream. A whole mountain range may be so raised across the course of a river, the plains on either side not being uplifted, and the river cutting down as fast as the uplift. Such a stream is said to be *antecedent*. The ridges through which these water

gaps occur were not, however, uplifted as individuals, and not necessarily as slowly as the streams cut down. The whole peneplain was uplifted, its drainage intact, and the streams then etched out the plains and gaps, as described above.

A somewhat different type of trellised drainage is produced by parallel faults (Priest Valley sheet, Cal.), either because of parallel dropped blocks, or as a result of erosion along crushed and brecciated zones (pp. 66, 129 and 191–192). This type is usually, however, less intricate and closely spaced than that resulting from pronounced folding of alternating hard and soft layers (Monterey sheet, Va.-W. Va.), the pattern on the main blocks between the rift valleys being notably dendritic. Parallel rift valleys are well shown on the San Mateo (Cal.) sheet, though the remainder of the drainage is quite lacking in the typical parallel arrangement or right-angled turns shown so well on the Vandiver (Ala.) sheet.

Closely spaced parallel streams down the steep slopes of certain mountain ranges are somewhat analogous to trellised drainage (Mt. Whitney sheet, Cal.). The parallelism becomes especially striking if they have been straightened by glaciation (Hamilton sheet, Mont.-Idaho). Consequent valleys down a mountain front, if they are not controlled by other structural features, will probably not show the characteristic right-angled turns so common in typical trellised drainage (Vandiver, Ala.) and the two features should not be confused. On the Hamilton sheet the right angles in stream courses suggest some structural control.

If harder rocks occur in small masses, such as igneous patches or bosses (Uvalde sheet, Tex.), isolated knobs or *buttes* commonly result which cannot be definitely recognized as of igneous origin from the topographic map alone. Their actual relief on the Uvalde sheet is undoubtedly related chiefly to erosion before the laying down of the terrace gravels shown on the geologic map, but is, nevertheless, due to superior hardness. Many of the buttes and mesas of the Tusayan (Ariz.) sheet are actually igneous, or capped with igneous rock, though on the map they

do not appear essentially different from those of Monument Valley (Henry Mountains sheet, Utah), which are capped with a harder sedimentary layer. It has already been pointed out (p. 63) that dikes may sometimes, because of superior hardness, result in narrow ridges (Spanish Peaks sheet, Colo.).

Further discussion of the effects of unequal hardness of rocks will be deferred to the section on the "Relation of Land Forms to Structure".

Additional maps illustrating the features described above

Rock terraces

Kaibab, Ariz.
Mt. Trumbull, Ariz.
Mesa de Maya, Colo.
Soda Canyon, Colo.
Timpas, Colo.
Mountain Home, Idaho.
Watrous, N. M.
Quincy, Wash.

Mesas

Marsh Pass, Ariz.
Elmoro, Colo.
Mesa de Maya, Colo.
Mesa Verde National Park, Colo.
Mt. Carrizo, Colo.
Soda Canyon, Colo.
Timpas, Colo.
Fort Custer, Mont.
Lamy, N. M.
Raton, N. M.-Colo.
Watrous, N. M.
Jordan Gap, Tex.
Tascotal Mesa, Tex.
Ishawooa, Wyo.

Regional escarpments

Mesa Verde National Park, Colo.
Red Mesa, Colo.
Independence, Kan.
Richmond, Ky.
Chillicothe, Ohio.
Hollow Springs, Tenn.
Tascotal Mesa, Tex.
Wellington, Utah.
Kendall, Wis.

Ridges on tilted rock

Vandiver, Ala.
Magazine Mountain, Ark.
Fort Collins, Colo.
Loveland, Colo.
Antietam, Md.-Va.-W. Va.
Saypo, Mont.
Plainfield, N. J.-N. Y.
Lykens, Pa.
Gerrardstown, W. Va.
Natural Bridge, Va.

Elbow and zigzag ridges

Vandiver, Ala.
Mt. Ida, Ark.
Loveland, Colo.
Rome, Ga.-Ala.
Winding Stair, Okla.
Everett, Pa.
Lykens, Pa.
Williamsport, Pa.
Marathon, Tex.
Dublin, Va.-W. Va.
Hancock, W. Va.-Md.-Pa.
Como Ridge, Wyo.

Water gaps

Vandiver, Ala.
Caddo Gap, Ark.
Hot Springs and vicinity, Ark.
Fort Collins, Colo.
Antietam, Md.-Va.-W. Va.
Saypo, Mont.
Everett, Pa.
Lykens, Pa.
Shippenburg, Pa.
Williamsport, Pa.

Dendritic drainage

Soda Canyon, Colo.
Gillespie, Ill.
Milo, Iowa.
Richmond, Ky.
De Soto, Mo.
Gothenburg, Neb.
Athalia, Ohio-W. Va.
Elk Point, S. D.-Neb.-Iowa.
Hollow Springs, Tenn.
Cameron, W. Va.-Pa.-Ohio.
Kendall, Wis.

Trellised drainage

Bessemer special, Ala
Vandiver, Ala.
Caddo Gap, Ark.
McAlester, Okla.
Lykens, Pa.
Millerstown, Pa
Ringgold, Tenn.-Ga.
Christianburg, Va.-W. Va.
Winchester, Va.-W. Va.
Beverly, W. Va.-Va.
Gerrardstown, W. Va.
Wardensville, W. Va.-Va.

Piracy and Adjustment.—

Maps

Springville, Ala.	Lykens, Pa.
Mesa Verde National Park, Colo.	Wind Gap, Pa.
Waipio, Hawaii	Maynardville, Tenn.
Lockport, Ky.	Clintonville, W. Va.
Pawpaw, Md.-W. Va.-Pa.	Gerrardstown, W. Va.
Todd Lakes, Mont.	White Sulphur Springs, W. Va.
Kaaterskill, N. Y.	Harpers Ferry, Va.-W. Va.-Md.

Whenever a divide is notably asymmetrical, the streams on the steeper slope, having a higher gradient and a greater cutting power, work headward at a more rapid rate and shift the divide, encroaching on the drainage areas of their neighbors of gentler gradient. This is to be seen in very striking fashion on the Mesa Verde National Park sheet (Colo.), on which the divide between Montezuma Valley and the south-flowing tributaries of Mancos River is being pushed southward by the steep north-draining gullies, at the expense of the gentler south-flowing streams.

In several cases the south-draining canyons can be traced north into notches in the escarpment that have resulted from this encroachment *beheading* the stream. Such is notably the situation on the head of Morfield Canyon, where Lone Cone (NW. ¼ sec. 8, T. 35 N., R. 14 W.) is all that is left of the tip of the divide at the junction of what was once two tributaries of the canyon, both of which have lost their upper courses as a result of the *recession* of the escarpment. Such *monoclinal shifting* of divides is one of the common features of the adjustments that take place in drainage during the course of a cycle. The beheading of Morfield Canyon seems to have been accomplished chiefly by the simple encroachment of the escarpment, and there is little evidence that any of its headwater tributaries were ever diverted as such into the opposing drainage.

A similar asymmetrical divide on the Kaaterskill (N. Y.) sheet is being pushed westward, the steep east-flowing streams encroaching on their gentler west-flowing neighbors, as the escarp-

ment retreats. In the process, however, somewhat different modifications occur than those noted on the Mesa Verde. For instance, even a casual examination of North and South Lakes (NE. rect.) and the gentle open valley leading westward from their outlet will convince one that they are really a part of the head of Gooseberry Creek, and that Kaaterskill Creek, working rapidly headward with its steeper gradient, tapped the valley and *captured* the waters from the lakes. Gooseberry Creek is said to be *beheaded*, that part of the stream that formerly flowed into the Schoharie, but now belongs to the Kaaterskill, is said to be *diverted*, and the process is termed *stream piracy*. The creek from the lakes to the Kaaterskill, with its acute angle on the down-stream side of the main creek, is a *barbed tributary*, and the elbow thus formed is an *elbow of capture*.

It also seems highly probable that that part of Sawkill Creek above Shady (S. cent. rect.) once followed the open valley north of Cooper Lake, westward into Beaverkill, but was captured by Sawkill working headward into the escarpment. A similar capture seems to have occurred at Plaat Clove P. O. (cent. rect.) and a further one is imminent at the same locality.

A fine example of a barbed tributary is to be seen on the Todd Lakes (Mont.) sheet, in the N. ½ sec. 11, T. 31 N., R. 44 E. Another occurs in the SW. ¼ sec. 5, T. 31 N., R. 45 E. A capture that will produce still another is imminent in sec. 12, T. 31 N., R. 45 E.

The above examples of piracy illustrate a type especially common along regional escarpments, on gently dipping beds, in which there is a softer layer capped with a harder, so that conditions are favorable for rapid sapping and retreat of the escarpment.

A very interesting type of stream capture is shown on the Waipio (Hawaii) quadrangle, where a large number of cases occur. The upland is drained by numerous small streams, probably initial consequent in origin. Into the upland plain a few deep canyons are cutting, and, as these lengthen and widen, they actually encroach upon and absorb the lower courses

of the smaller upland drainage lines, the headwaters of which remain intact, but which turn abruptly at the brink of the larger canyons and discharge over falls or rapids at nearly right angles to their former courses, resulting in striking elbows of capture. Illustrations are to be found on most of the larger gorges.

Another type of piracy is shown on the Lockport (Ky.) sheet. Sawdridge Creek appears to have at one time flowed through the valley of Pond Creek (N. cent. rect.) but to have been captured at Monterey by the cutting toward each other of the scarp slopes of opposing meanders. This explanation is supported by the fact that the lower part of Sawdridge Creek is distinctly intrenched, as though the gradient had been increased by shortening its course. A somewhat similar case probably occurs in the central rectangle of the Pawpaw (Md.-W. Va.-Pa) sheet, Fifteen Mile Creek having been shortened by the lateral swing of the Potomac River.

Still another sort of region especially favorable to piracy is one of parallel ridges and valleys on highly tilted, alternating hard and soft rocks. The classical example of such piracy, described in a number of standard texts, is that of Snickers Gap (Harpers Ferry sheet, Va.-W. Va.-Md.). At a much earlier stage in the history of the area, the headwaters of Beaverdam Creek originated west of Blue Ridge, emerging through Snickers Gap. To the northward, Potomac River crossed through a similar gap, but, since that stream was of a much larger volume than Beaverdam, it could lower its notch more rapidly, and allow its subsequent tributary on the soft rock, the then youthful Shenandoah, to work back toward the headwater area of Beaverdam, which it finally tapped. The headwaters were diverted, Beaverdam was beheaded, and Snickers Gap changed from a water gap to a *wind gap*.

A far more striking example, probably more apparent chiefly because better mapped, is to be seen on the Wind Gap (Pa.) sheet. Obviously, a stream at one time passed through Wind Gap and the gap at Saylorsburg, and this stream has been tapped at two or more points by subsequent streams working headward on the softer layers, so that now the old transverse river has ceased

to exist, its waters diverted into other drainage systems leaving these striking wind gaps.

On a peneplain, which commonly has deep residual soil, are usually many streams that are but little controlled by structure. An uplift which allows these streams to start down-cutting soon results in their being superimposed through the soil onto the hard-rock ridges in very irregular fashion. Such superimposition may also result from submergence, and the laying down of a mantle of marine coastal-plain beds on which streams, after emergence, may wander freely over the hard-rock layers. As the streams intrench themselves, they begin to cut water gaps across the hard rocks, and at the same time to widen their plains on the softer beds (pp. 101–102). Subsequent tributaries of the larger streams etch back on the soft belts and capture the smaller transverse water courses, which are unable to lower their notches in competition with their larger neighbors. Thus in time the smaller transverse streams are all destroyed, only the master streams being able to hold such courses, so that, finally, the region becomes one of a few trunk rivers that may be transverse to the structure, with the tributaries chiefly adjusted to the soft rocks. In this process, which is termed *structural adjustment of drainage*, stream piracy plays a large part.

Thus, on the Maynardville (Tenn.) sheet many transverse streams cross Bull Run Ridge (SW. rect.) and Pine Ridge (W. cent. rect.) through water gaps. As time goes on, however, the larger of these streams will, by the process of piracy outlined above, destroy the smaller, until only one or two of these gaps will carry running water, and the drainage will more nearly parallel the ridges. This, for example, has already happened along Beaver Creek Mountain in the central rectangle of the Springville (Ala.) sheet, and its extensions as Oak Ridge and Greens Creek Mountain. Of the nine distinct gaps in this ridge, only one now accommodates a transverse stream, the one where Coosa River crosses at Greensport. The others have been abandoned, as a result of the development of the two subsequent streams, Shoal Creek and Beaver Creek.

This adjustment of the streams to the soft rocks is very complete on the Lykens (Pa.) sheet, the long, regular hard-rock ridges being remarkably free from transverse streams and water gaps. On the Gerrardstown (W. Va.) sheet, there are no streams transverse to the main ridges, though their former existence is attested by several wind gaps in North Mountain, one of which (Mills Gap) is a rather notable notch, and must have persisted later than the others as a water course.

In limestone regions, subterranean diversions of drainage are much more common than is generally realized. Frequently, these are too small to be shown on the published topographic maps. Splendid examples, on a large scale, occur on the Clintonville (W. Va.) sheet. An open valley, starting at the east end of the fifty-fifth parallel, apparently once carried a tributary to the head of Mill Creek (SE. rect.), but now the stream in its upper course disappears into a sink hole, and for many miles the valley carries no stream, is occupied by many sinks, and has a gradient sloping north in some places and south in others.

Sinking Creek (NE. rect.) seems at one time to have flowed over a low saddle, but has been diverted through the tunnel at the east edge of the sheet, since which time its valley has lowered appreciably. In the east central rectangle the same stream plunges into a sink, flows underground for some distance, reappears in the bottom of another sink, then disappears and finally emerges at Piercy's Mill.

The same sheet shows ordinary surface piracy between Cleveland School and Lewis School (SW. rect.), the eats-flowing stream encroaching on the head of Meadow River, as shown by the two barbed tributaries just west of bench mark 2306.

An especially striking example of underground diversion is that of Culverson Creek (NW. rect., White Sulphur Springs sheet, W. Va.). This stream probably once followed the open valley past Bethel School, but has been diverted into an underground channel at a sufficiently lower level so that it has now intrenched itself below the valley it abandoned. The open valley east of Unus, sloping westward, united with Burns Run to join a south-

west-flowing stream about at the figures 2192. That part of the present river course between this figure and the place where the water goes underground is reversed in direction, and Burns Run is a barbed tributary. See also pp. 25–26.

Additional examples of piracy and adjustment

Fort Payne, Ala.-Ga.
Caddo Gap, Ark.
Hot Springs and vicinity, Ark.
Capitola, Cal.
Cuyamaca, Cal.
Elsinore, Cal.
Mt. Goddard, Cal.
Olancha, Cal.
Ramona, Cal.
San Luis Rey, Cal.
Loveland, Colo.
Antietam, Md.-Va.-W. Va.
Frostburg, Md.-W. Va.-Pa.
Slide Mountain, N. Y.
Altoona, Pa.
Ebensburg, Pa.
Millersburg, Pa.
Pine Grove, Pa.
Crossville, Tenn.
Hollow Springs, Tenn.
Morristown, Tenn.
Ringgold, Tenn.-Ga.
Tascotal Mesa, Tex.
Wellington, Utah.
Pasco, Wash.
Priest Rapids, Wash.
Ishawooa, Wyo.

Evidences of More than One Cycle.—

Maps

Diamond Creek, Ariz.
Marsh Pass, Ariz.
Tusayan, Ariz.
Yosemite, Cal.
Brownsville, Ky.
Lockport, Ky.
Holyoke, Mass.-Conn.
De Soto, Mo.
Forsyth, Mo.
Versailles, Mo.
Monadnock, N. H.
Raton, N. M.-Colo.
Kaaterskill, N. Y.
Poughkeepsie, N. Y.
West Point, N. Y.
Gastonia, N. C.
Hickory, N. C.
Morganton, N. C.
Mount Mitchell, N. C.
Statesville, N. C.
Delaware Water Gap, Pa.-N. J.
Harrisburg, Pa.
Latrobe, Pa.
Lykens, Pa.
Pikeville special, Tenn.
Henry Mountains, Utah.
Gerrardstown, W. Va.
Harpers Ferry, Va.-W. Va.-Md.
Martinsburg, W. Va.-Va.-Md.
Winchester, W. Va.-Va.
Wausaw special, Wis.

The planation history of a locality that has passed through any part of a cycle of erosion may be interrupted by uplift

which will invigorate the streams and *rejuvenate* the area, initiating a new cycle. Unless, however, the region has progressed far enough in the cycle so that considerable areas are reduced to base level, the rejuvenation may not be conspicuous. But if rather broad portions have been so reduced before the uplift occurs, the rejuvenation will set the streams at work intrenching themselves in the plain they have formed. The evidence that such a plain has actually been cut by erosion at base level, and is a true peneplain, is greatly strengthened if it truncates upturned hard and soft rocks, since under no other conditions than at base level can a series of streams cut a plain across tilted hard and soft strata. In such a case the soft beds are worn to base level first, and erosion on them practically ceases, while that on the hard rocks proceeds more slowly until they, too, are reduced.

The Gastonia (N. C.) sheet presents an excellent example of a former very perfect peneplain, thus uplifted and now in its second cycle. This area is known, from evidence not on the topographic map, to be one of crystalline rocks of very complex structure. Nevertheless, the interstream divides all rise uniformly to accordant heights, which average about 800 to 850 feet in the southeast and nearly 1,000 feet in the northwest part of the map. The character and the perfection of this peneplain can best be understood by imagining all the present valleys filled to the level of the existing divides. The region would then be a nearly featureless plain—a peneplain, sloping gently southeastward and broken only by two conspicuous low *monadnocks*, Spencer Mountain and Pasour Mountain.

If, now, one imagines the region lowered until this plain is at base level, the resulting condition will be that of the area at the time of the uplift which initiated the present cycle of erosion. The uplift amounted to at least 200 feet, as indicated by the depth to which the main streams are now intrenched, and was apparently slightly greater at the northwest than at the southeast. Since the uplift, dissection has progressed to late youth. The narrow fringes of flood plain along the main rivers represent

about the level at which, given time enough, a second peneplain similar to the first would be developed.

The dissected peneplain just described can be recognized over most of the Piedmont area of the eastern United States. Its features and its relation to the high Appalachians on the west are well exhibited on the Statesville, Hickory, Morgantown, and Mount Mitchell (N. C.) sheets. The Statesville sheet shows the old peneplain at about 800 to 1,000 feet with but a single monadnock in the northwest corner. The Hickory sheet was 90 per cent peneplain, but with numerous monadnocks rising to elevations of 1,500 to 2,500 feet above sea level. The Morgantown sheet is divided about half and half between the peneplain and numerous high ridges, at altitudes of 2,500 to 4,000 feet, of very irregular trend, which indicate the complexity of the geologic structure. The Mount Mitchell sheet is a complex of irregular ranges often more than 5,000 feet high, and shows mere traces of the old peneplain.

The northern Appalachians show clear evidence of having undergone two periods of base leveling, of which the first was probably much the more complete. The Lykens and Harrisburg (Pa.) sheets are typical. Each presents a conspicuous series of high, sharp ridges, or mountains, which undoubtedly represent tilted layers of hard rocks. These ridges differ remarkably, however, from those just described on the Morgantown and Mount Mitchell (N. C.) sheets. Thus, on the Lykens sheet each ridge has a nearly even, uniform crest line, and the several ridges rise to nearly accordant heights, averaging 1,300 to 1,500 feet. At places, moreover, they show distinctly flat, beveled tops, as at Berry Mountain and Short Mountain (SW. rect.). On the Harrisburg sheet the crest lines average 1,300 to 1,600 feet, and Third Mountain shows a wide, flat, beveled top. Clearly, if we should fill in all the lowlands between these high ridges we would have again a plain, or peneplain, with a southeast slope, just as on the North Carolina sheets, and these ridges of uniform crest lines with beveled tops undoubtedly represent

the remnants of such a peneplain, of which much less is left than in the Carolina area.

It is inconceivable that in the folding process these various mountains, parts of several different folds, could have been raised to so nearly uniform heights. It is equally improbable that on folds of unequal height erosion could have produced such a level under any conditions other than by peneplanation at base level, for down-cutting on folded rocks of unequal hardness at any stage above that level would be characteristically selective and uneven.

The second, later and lower peneplain is well developed southeast of Blue Mountain, Harrisburg sheet, where all the hills have accordant and rather flat tops rising about 500 feet above sea level. The lowland northwest of Peters Mountain and the valleys between the various ridges undoubtedly were formed at the same time. This peneplain was less perfect than the higher and older one, for the various mountains constitute unreduced remnants or monadnocks of harder rock above it. It was sufficiently perfect, however, that its largest streams, especially Conodoquinet Creek, developed very pefect meanders on its surface. Since its formation, further uplift has occurred, resulting in renewed dissection, and in the intrenching of the meandering streams. On the Lykens sheet, this second peneplain is represented by the lowlands between the ridges, such as that between Mahantango and Line mountains at about 1,000 feet.

The erosion history of the Harrisburg region may be summed up as follows: After the folding came reduction of a large region to nearly featureless old age, at or near sea level. This was followed by uplift of the whole region (not just the ridges) about 800 feet, with initiation of a new cycle. The soft rocks were again reduced to base level, but the harder rocks, etched into relief, still persist as long, steep monadnocks, showing that the second cycle was less complete than the first and had probably progressed no further than late maturity or early old age. Another uplift of about 200 feet initiated the third or present cycle, which has not progressed beyond late youth.

A similar erosion history has prevailed over most of the Appalachian and New England regions, with two outstanding periods of peneplanation, though other and intermediate levels have been described in some localities. Of course, the amount of uplift differs in various sections, but otherwise the events follow in about the same succession.

The higher level has been termed the Cretaceous peneplain, in the belief that it was completed in Cretaceous time, and the name persists, though grave doubt now attaches to its applicability. Similarly, the lower widespread level has been termed the Tertiary peneplain. Perhaps more satisfactory is the use of local geographic names to indicate these features. The older and higher level has been rather widely termed the Kittatinny peneplain, from Kittatinny Range (Delaware Water Gap sheet, Pa.-N. J.), the crest of which constitutes a remnant of this widespread upland.

The lower or Tertiary level in Pennsylvania has been termed the Harrisburg peneplain, because it is so well developed in the Harrisburg area. It is even better illustrated in the Shenandoah Valley, whence it is also called the Shenandoah peneplain. The Harpers Ferry (Va.-W. Va.-Md.) and Winchester (Va.-W. Va.) sheets show it particularly well. The higher (Cretaceous) peneplain is represented by Blue Ridge (1,300 to 1,900 feet), Little North Mountain (up to 1,700 feet), Shelby Mountain (up to 1,900 feet), Great North Mountain, Cacapon Mountain (2,500 feet and over), and numerous mountains at about 2,000 feet. Some of these doubtless represent once accordant ridges now somewhat irregularly reduced, as suggested especially by North Mountain and Sleepy Creek Mountain on the Gerrardstown (W. Va.) sheet (a detailed resurvey of the northeast fourth of the Winchester sheet). The highest summits probably represent monadnocks above this peneplain, as suggested by the highest point of Third Hill Mountain (Gerrardstown sheet), above 2,200 feet.

The Shenandoah peneplain was a wide lowland on weak rocks over which the Shenandoah and Potomac rivers meandered freely.

The effect of superior hardness is strikingly shown at Harpers Ferry, by the narrow gap these rivers were able to cut through Blue Ridge while they were developing the wide lowland above that point. The area shows slight uplift and intrenchment of the rivers below the Shenandoah level, as at Harrisburg. The intrenching is not particularly obvious on the Harpers Ferry and Winchester sheets, because of the large interval used, but is clearly brought out on the Gerrardstown (W. Va.) and Martinsburg (W. Va.-Va.-Md.) sheets.

A New England upland level which truncates complexly folded rocks is shown in the south half of the Monadnock (N. H.) sheet at about 1,200 to 1,300 feet, surmounted by Mount Monadnock, from which this type of residual hill gets its name. Since this peneplain was completed, it has been raised, dissected to maturity, and glaciated.

On the Holyoke (Mass.-Conn.) sheet, there is a western upland, averaging 1,200 or 1,300 feet at the south border of the map and 1,300 or 1,400 feet at the north border, which represents the same upland surface already described. On the east is a lowland approximately at 200 feet, and below this the river is intrenched over 100 feet. The western upland corresponds to the so-called Cretaceous peneplain. After its completion, the region was uplifted 1,000 feet or more, and the eastern lowland etched out of softer rock to a peneplain above which the Holyoke Range and Mt. Toby rose as monadnocks, while the western highland on hard rocks was but little reduced. A further uplift of 100 feet or more has allowed Connecticut River to intrench itself in this lower plain, which represents the so-called Tertiary level.

The western upland is in early maturity on which glaciation has superimposed youthful features. No part of it on the Holyoke sheet had advanced far enough in the cycle during the making of the Connecticut Valley lowland, so that the Tertiary level can be detected as a stage in its history. In some localities, however, even rather narrow valleys show a fringe of lower peneplain. Along the Hudson River (West Point sheet, N. Y.), the platform on which West Point and Garrison (W. cent. rect.)

stand is a narrow peneplain fringe at an elevation just under 200 feet. On the map this might be mistaken for an alluvial terrace, or possibly for a rock terrace held up by a horizontal layer of some hard formation. In the field, however, the bench is clearly seen to bevel the rock structure. At Storm King, where the rock is very resistant, no such level is present, but northward (Poughkeepsie sheet, N. Y.) from the highlands, where the rock is less resistant, the peneplain widens out into a rather extensive lowland about 200 feet above sea level, which is supposed to correspond to the Connecticut Valley or so-called Tertiary peneplain.

The Wausaw special (Wis.) affords a good illustration of the widespread peneplain of northern Wisconsin, at an elevation of 1,400 to 1,500 feet, above which Rib Hill stands as a pronounced monadnock, and into which Wisconsin River has been intrenched some 200 or 300 feet. The evidence from the map alone, however, is not sufficient to prove that this is a true peneplain. Although the rock is actually largely crystalline, the drainage pattern is such as might result on a stripped plain controlled by a horizontal layer of very hard rock. That this is not the real explanation is shown not from the topographic map, but from the geologic map of Wisconsin.

As suggested in the preceding paragraph, in a region consisting of alternating hard and soft formations in horizontal position, evidences of peneplanation are usually much less convincing than in a folded area. A hard layer of rock, overlain by a much softer one, may serve as a temporary base level for most of the streams, particularly the smaller ones. As soon as these have cut down to the hard layer, lateral erosion becomes relatively far more conspicuous than deepening. The result is that the soft rock is stripped off, reducing the region to a condition more or less amalogous to late maturity or early old age, before erosion gets through, or even well into, the hard layer. Such a plain may resemble a peneplain in most of its essential features, though it may have been formed far above ultimate base level. A topographic form of this sort is termed a *stripped structural plain*. The ordinary rock terrace produced by horizontal beds

or harder material bears the same relation to a stripped structural plain that the narrow rock-cut bench, beveling structure along the Hudson (West Point sheet, N. Y.) bears to a peneplain. In other words, it represents the beginning of the process.

The narrow terrace at 2,000 feet on the Colorado River (Diamond Creek sheet, Ariz.) is probably controlled by a hard horizontal layer, and it seems more than likely that the broader one at 4,250 feet is of the same order, only more advanced. The symmetry of these terrace widths on opposite sides of the valley (p. 100) suggests that they are controlled by hard layers of rock, and are not partial peneplains. If by this process it is reasonable to account for terraces from 4 to 6 miles wide, then we may fairly assume that the process can go much farther, and leave numerous isolated buttes and mesas, such as those of Monument Valley (SE. rect., Henry Mountains sheet, Utah), which, even though the map fails to show it, are clearly seen in the field to be remnants left behind by the recession of a very prominent escarpment (see adjacent portion of Marsh Pass sheet, Ariz.).

No great stretch of the imagination seems necessary to go a step farther, and assign the buttes and mesas of the Tusayan (Ariz.) sheet to the same process, that is, to remnants above a stripped plain, even though they have been considered by others as monadnocks rising above a broad and nearly perfect peneplain. There does not seem to be any possibility of deciding from the topographic map alone between these two interpretations. One should certainly be cautious, in a region of horizontal rocks, about asserting that every upland plain above which remnants rise, or into which streams are intrenched, is necessarily a peneplain.

It has been suggested that the remarkably even upland in the Ozarks (De Soto sheet, Mo.) is a stripped structural plain, inasmuch as the rock formations are essentially horizontal. There is certainly no evidence, from the topographic sheets alone, to decide between peneplain and stripped plain in this region. Anyone, however, who is familiar with the geology knows that in the De Soto quadrangle, for example, this plain is dipping much more gently than the rock strata, so that it distinctly

bevels structure, truncating faults of several hundred feet displacement, and resting on much older beds in the southwest corner of the sheet than in the northeast. This could certainly be accomplished only by peneplanation.

In one sense, the semblance of late maturity or old age developed on a horizontal stratum of very hard rock represents a nearly completed cycle, just as does a peneplain. Nevertheless, our ideas are clarified by distinguishing the two processes, and by actually discriminating between their results, wherever possible, since they involve a rather different history. In regions like the Appalachians, New England, or northern Wisconsin, already cited, or in the Rocky Mountains or other folded ranges of the west, where the upland clearly truncates the structure, interpretations are not open to much doubt. In regions of more nearly horizontal rocks, larger areas must be examined, but if the plain is found to bevel the strata, even at a low angle, the evidence for peneplanation is usually good, though not often will it be possible in such a case to determine the facts from the topographic map alone, as can be done where the topography gives evidence of folded strata.

A very striking example of two levels produced by erosion is to be noted on the Raton (N. M.-Colo.) sheet, the lower at about 6,500, the higher above 8,000 feet. That these high mesas are remnants of a once continuous upland, which has been carved away by erosion, admits of no doubt. That the lower plain is a peneplain in the true sense is open to considerable doubt, since it is perfectly possible that it is held up on the surface of a hard layer from which overlying softer beds have been stripped. A careful study in the field might show that the lower plain bevels across the strata, a condition indicative of peneplanation. On the other hand, if the plain is parallel to the strata, the probabilities are that it is structural though even then the possibility of peneplanation and uplift would have to be considered.

One of the particularly striking features of a region in a second or third cycle of erosion is the presence of meanders without an appropriate flood plain. If streams in late maturity or old age

meander broadly over an extensive flat, and the cycle is interrupted by uplift, these streams will tend to resume active down-cutting, and, though still occupying their meandering courses, will soon be countersunk into the former plain in narrow gorges or canyons, without flood plains.

It is true that any stream in youth develops occasional bends, and, if the region is flat enough, even small meanders. As the stream intrenches, these cut on the outside of the curve, and tend to perfect themselves, so that an occasional meander may occur on a stream that has never been mature. So far as we know, however, true meander belts comparable to those of full maturity and old age are not developed in this manner. Such meanders as those along the Potomac River on the Martinsburg (W. Va.-Va.-Md.) sheet, or along Conodoquinet Creek on the Harrisburg (Pa.) sheet are quite certainly indicative of former flood-plain conditions, and are true *intrenched meanders*, inherited from a previous cycle of erosion.

In areas of flat-lying rocks, particularly where there are no notable erosion remnants above the general surface, intrenched meanders afford the most striking evidence of a former cycle, as on the Versailles and Forsyth (Mo.) sheets. Fine examples are also to be seen on the Brownsville (Ky.) and Latrobe (Pa.) sheets. Within these intrenched meanders, the narrow necks of upland are often notably steeper on one side, the *cut bank* or *scarp slope*, and gentler on the other, the *slip-off slope*. The slip-off usually points in the direction of stream flow, as east of Bow (N. cent. rect.) on the Latrobe (Pa.) sheet or at Lecompte Bottoms (cent. rect.) on the Lockport sheet (Ky.).

At Craddock Bottom (cent. rect., Lockport sheet) is a very fine abandoned meander scrap. An abandoned intrenched meander occurs in the southeast quarter of the south central rectangle, possibly a subterranean diversion, since the rocks near river level are known from the abundant sinks to be soluble limestone. Such a subterranean cut-off of a large intrenched meander on the Niangua River in Missouri is now in process of forming, though no maps are available to show

it.[1] A high-level meander scarp of an intrenched meander is well developed near Gratz (NW. rect., Lockport sheet). There has been considerable intrenching of the river since it was abandoned, its floor now forming a rock bench (note the sink hole) some distance above the present valley bottom.

Although it is possible for a stream to meander on a stripped plain and finally to intrench itself, in cutting through the hard layer, it is still probable that any great extent of intrenched meandering stream indicates at least partial peneplanation and uplift.

Still another evidence of a second cycle may be seen in upland topography distinctly more mature than the present dissection by deeper canyons working back into it. This is well shown on the Kaaterskill (N. Y.) sheet, the dissection of the upland being at least early mature with respect to the west-flowing streams, but very youthful with respect to Plattkill and Kaaterskill creeks on the east-facing escarpment. On the Pikeville special (Tenn.) there is fairly mature shallow dissection on the top of Walden Ridge, although the upland is very young with respect to the canyon of Richland Creek and the Sequatchie Valley. The same situation is exhibited on the Yosemite (Cal.) sheet, the upland of which is maturely dissected with a network of valleys the bottoms of which lie far above the main canyons, and the upland is still very young with respect to its present cycle.

Other maps showing evidences of more than one cycle

Peneplains truncating structure

Fort Payne, Ala.-Ga.	Morgantown, N. C.
Morrilton, Ark.	Nantahala, N. C.-Tenn.
Farmington, Conn.	Altoona, Pa.
Dahlonega, Ga.-N. C.	Bedford, Pa.
Hagerstown, Md.-Pa.	Lykens, Pa.
Pawpaw, Md.-W. Va.-Pa.	Wind Gap, Pa.
Greylock, Mass.-Vt.	Bristol, Va.-Tenn.
Hawley, Mass.-Vt.	Lexington, Va.
Durham, N. Y.	Staunton, Va.-W. Va.

[1] Dake, C. L., and Bridge, J., "Subterranean stream piracy in the Ozarks"; Univ. of Mo. Sch. Mines and Met., *Bull.*, vol. 7, no. 1, 1923.

Intrenched meanders

Fort Payne, Ala.-Ga.
Axial, Colo.
Harrodsburg, Ky.
Mammoth Cave, Ky.
Pawpaw, Md.-W. Va.-Pa.
Sullivan, Mo.
Tuscumbia, Mo.
Wyandotte, Okla.-Mo.-Kan.
Confluence, Pa.
Franklin, Pa.
Huntingdon, Pa.
McMinnville, Tenn.
La Sal, Utah-Colo.
Eagle Rock, Va.
Arnoldsburg, W. Va.
Beckley, W. Va.
Elizabeth, W. Va.
West Union, W. Va.

Abandoned intrenched meanders

De Soto, Mo. (N. cent. rect.).
Eminence, Mo. (N. ½ sec. 27, T. 29 N., R. 4 W.).
Brownsville, Pa. (cent. and E. cent. rects.).
Alderson, W. Va. (NE. rect.).
Belleville, W. Va.-Ohio (NE. rect.).
Hanging Rock, W. Va. (N. cent. rect.).
Parsons, W. Va. (NW. rect.).

RELATION OF LAND FORMS TO STRUCTURE

THE BASIS FOR TOPOGRAPHIC REFLECTION OF STRUCTURE

Maps

Vandiver, Ala.	Asheville, N. C.-Tenn.
Shinumo, Ariz.	Mount Mitchell, N. C.-Tenn.
Crystal City, Mo.-Ill.	Kiefer, Okla.
Monterey, Va.-W. Va.	

In previous discussions (pp. 100–104), much stress has been placed on the relative resistance of the various rock units. With insignificant exceptions, structure may be deciphered from topography only in regions of alternating weak and resistant strata. In areas where the rocks are folded, but are of nearly equal resistance to weathering and erosion, little or nothing can be done in interpreting structural conditions from the topography; in other words, there is no topographic expression of the structure.

For example, the folding and faulting are far more intense on the Asheville and Mount Mitchell (N. C.-Tenn.) sheets than on the Monterey (Va.-W. Va.) or Vandiver (Ala.) quadrangles. Yet on the two latter, the structure profoundly modifies—in fact, essentially controls—the topography; whereas on the Asheville and Mount Mitchell sheets only here and there do narrow ridges faintly suggest folding. These, if compared with the geologic maps of the same areas, are seen to be chiefly accidental rather than related to structure. For example, a comparison of Green Mountains (N. cent. rect., Mount Mitchell sheet) with the geologic map (Folio 124) shows that they are not parallel to the structure, but cross belts of several different kinds of rock, so that they do not seem in any way to be related to any visible fold or fault. The same is true of practically all the ridges on the map. Nearly identical conditions obtain on the Asheville sheet (Folio 116). Elk Mountains (SE. rect.) are composed of the same formation as the lowland on either side, and are at right angles to the general strike of the folding. Hanlon Mountain (S. cent. rect.) is crossed diagonally by a very narrow belt of a formation different from that in the rest of the mountain.

Spring Creek Mountain (cent. rect.) is transverse to several belts of rock, and clearly does not reflect folding or faulting. In fact, the only range on the sheet that is definitely related to structure is Meadow Creek Mountains (NW. rect.) held up chiefly by quartzite, with limestone on either side to produce a lowland.

This lack of relation between topography and structure results from insufficient differences in resistance to allow etching out of some formations from among others. Quite the reverse case is illustrated in the Monterey (Va.-W. Va.) area, in which practically all the ridges and valleys are parallel, and each corresponds to the strike of a formation. Many of the larger valleys are etched out on limestone, many of the more prominent ridges are quartzites standing in relief (geological map, Folio 61).

The same contrast in more moderately dipping beds is to be seen in the Kiefer (Okla.) and Crystal City (Mo.-Ill.) sheets. On the Kiefer quadrangle a west regional dip of less than 1° results in a striking regional escarpment (pp. 135–148) due to a harder layer capping softer rock. Across the Crystal City sheet just as steep a regional dip to the northeast produces only the faintest hint of an escarpment, simply because there are not sufficient differences in rock resistance to bring about the necessary *differential erosion.*

Within the Grand Canyon (Shinumo quadrangle, Ariz.) "Granite Gorge", chiefly below 3,000 feet in elevation, shows very little tendency toward the formation of rock terraces, in striking contrast to their remarkable development in the upper walls. This is because the inner gorge is cut in massive igneous and metamorphic rocks which are essentially homogeneous, whereas the upper walls are trenched in nearly horizontal sedimentary rocks arranged in alternating hard and soft strata.

It may be well to repeat, by way of summary, that our ability to read structure from topography, either in the field or on contour maps, is almost wholly dependent on the presence of a series of alternating weak and resistant rocks, which will allow certain beds to be etched into such relief as will bring out the lines of arrangement of the formations.

If all of the rocks in any region are highly resistant, but in equal degree, or if they are all weakly resistant, but equally so, the tendency is to produce a relief wholly independent of structure.

The presence of thin beds of more easily eroded material does not, as a rule, exert a strong topographic control, but if the softer beds are thick, even though the harder beds are equally so, the structure is brought into relief. In a thick series of soft rocks, especially if they are dipping at low angles, a very thin, hard layer may produce much effect on the character of the land surface, because it caps and protects broad areas of softer material; but, as the dip steepens, a thin, hard layer gradually loses its relative importance and produces only minor topographic effects.

A hard sandstone 10 feet thick in a series of 500 feet of soft shales may, if the beds dip at low angles, produce mesas or escarpments (p. 100) of considerable extent, whereas the same thin bed in vertical or nearly vertical position may produce only a narrow inconspicuous ridge that would not show on the ordinary topographic sheet.

Naturally, in areas which are deeply buried under glacial drift, dune sand, or river alluvium, there is little opportunity for topographic reflection of structure, no matter what differences of hardness may exist in the buried formations.

DRAINAGE PATTERNS AND STRUCTURE

Maps

Vandiver, Ala.
Marsh Pass, Ariz.
Caddo Gap, Ark.
Colfax, Cal.
Cucamonga, Cal.
Jackson, Cal.
Kaiser, Cal.
Kaweah, Cal.
Marysville Buttes and vicinity, Cal.
Olancha, Cal.
Priest Valley, Cal.
San Mateo, Cal.
Shasta special, Cal.
Tehipite, Cal.
Tujunga, Cal.
Rangely, Colo.
Island of Kauai, Hawaii.
Waipio, Hawaii.
Chesterfield, Mass.
Saypo, Mont.
Todd Lakes, Mont.
Monadnock, N. H.
Cooperstown, N. Y.
Oneonta, N. Y.
Asheville, N. C.-Tenn.
Mount Mitchell, N. C.-Tenn.
Atoka, Okla.
Crater Lake National Park, Ore.
Mt. Hood, Ore.-Wash.
Lykens, Pa.
Millerstown, Pa.
Quakertown, Pa.
Briceville, Tenn.
Greenville, Tenn.-N. C.
Hollow Springs, Tenn.
Escalante, Utah.
San Rafael, Utah.
King William, Va.
Monterey, Va.-W. Va.
Natural Bridge, Va.
Connell, Wash.
Walla Walla, Wash.
Blue Mesa, Wyo.

In a region in which the rocks were perfectly homogeneous in all birections over large areas, initial consequent streams (p. 101) would take the direction of slope of the newly exposed land surface. Insequent tributaries would form, and a perfectly dendritic pattern of drainage would ultimately result (p. 101). No amount of uplift and intrenching would in any way modify or disarrange this pattern, so long as the uplift were uniform. This condition is attained in almost ideal perfection on large areas of massive igneous rocks, and is strikingly exemplified on the north third of the Cucamonga (Cal.) sheet, and over a large part of the Tujunga (Cal.) sheet, where the topography is of distinctly fine texture. Slightly coarser texture on granite is exhibited on the Olancha, Kaweah, Tehipite, and Kaiser (Cal.) sheets, in which areas there has been some recent glacial modification.

Suppose, now, that, instead of a perfectly homogeneous mass of rock we have a series of horizontal stratified rocks with somewhat variable composition, but with all the strata essentially equal in resistance to weathering and erosion. The type of drainage outlined above would again result.

Let us assume, now, that such a series, alternating in composition but equal in resistance to agents of destruction, were to be folded up into a series of long, narrow, parallel synclines and anticlines. The initial consequent drainage would consist of master streams following the pitch of the synclines, and short tributaries nearly at right angles down the slopes of the anticlines. To this extent, the drainage would show a trellised effect. As new tributaries worked back, however, they would encounter no unequal resistance and no structural control, and would be insequent in pattern. As the region progressed toward late maturity or old age, and the streams began to meander widely, the original trellised effect would be largely effaced. With subsequent uplift and intrenching, new tributaries would be strictly insequent, and there would result a drainage that was essentially dendritic, even though the rocks were highly folded.

Unusually good examples of very highly folded areas in which structure exerts little control over topography, chiefly because there are not sufficient differences in hardness of the various strata, are to be seen on the Asheville and Mount Mitchell sheets (N. C.-Tenn.), the Jackson and Colfax sheets (Cal.), and the Chesterfield (Mass.) and Monadnock (N. H.) sheets.

If we assume a series of stratified rocks, certain members of which are highly resistant to erosion and others of which are attacked much more readily, and imagine these in perfectly horizontal position, subjected to the agencies of ordinary erosion, the initial consequent streams will still develop in the direction of the original slope of the surface. Again, the tributary streams, all working on a single formation because of the horizontality, will feel no structural control whatever, for the reason that they are all working in the same sort of material, and they will be typically insequent, and the characteristic dendritic pattern of

drainage will result. This is essentially the condition on the King William (Va.) and Todd Lakes (Mont.) sheets.

A dendritic drainage pattern may, then, result from erosion on homogeneous material, such as massive igneous rocks, or on highly folded rocks of varying composition, provided they are of about equal resistance to erosive agents, or on beds of equal or unequal hardness in horizontal position. There do not appear to be any dependable criteria by which these various dendritic patterns may be distinguished, from the nature of the topography alone without a knowledge of the geology. It is, perhaps, worth while to point out that intense metamorphism tends to obliterate original differences of hardness in sediments, so that highly metamorphosed regions of intense folding are likely to show essentially dendritic patterns, except along belts of limestone, which usually result in lowlands.

If, however, our series of stratified rocks of alternating, strongly resistant, and easily eroded formations be tilted considerably and then eroded, the resulting topography will be strikingly different. In the earliest stages, the synclines will be occupied by initial consequent streams flowing in the direction of pitch. Short streams nearly at right angles to the folds will flow down the anticlinal slopes, and will result in a sort of trellised drainage, just as with rocks of equal resistance.

Because of their elevated position, and partly perhaps because of shattering in the folding process, the anticlinal crests will be attacked more vigorously than adjacent areas. As soon as erosion has cut through any harder layer into a softer one, at the crest of the fold, a longitudinal valley will tend to form along the axis of the anticline, draining out through a notch in the harder layer on the side of the fold (Fig. 13 *A*). This process will be general over the folded area, with longitudinal streams on both synclines and anticlines, and with crosswise or transverse streams nearly at right angles to them breaking across the hard layers in water gaps. By the process of stream piracy already described (pp. 106–111), the smaller transverse streams will be eliminated, so that the drainage pattern will consist of a few trunk

streams which may break through the hard-rock ridges in water gaps; but with a large proportion of the tributaries, and even large sections of the main streams themselves, occupying subsequent valleys, parallel to the rock structure, but breaking across it in occasional right-angled or transverse portions.

Trellised drainage patterns of this type are characteristic of considerably folded regions of alternating hard and soft strata, and are well illustrated in the Lykens (Pa.), Millerstown (Pa.), Monterey (Va.-W. Va.), Natural Bridge (Va.), Vandiver (Ala.), and Caddo Gap (Ark.) sheets. The contrast between dendritic drainage on horizontal sedimentary beds, and typical trellised drainage, is well shown on the Briceville (Tenn.) sheet (Fig. 7). The Greenville (Tenn.-N. C.) sheet affords a contrast between dendritic drainage on intensely disturbed sedimentary and crystalline rocks of about equal hardness (SE. rect.), and trellised drainage on folded alternating hard and soft rocks (NW. part of map).

Parallel faults may produce parallel ridges and valleys in any one of several ways. They may bring rocks of unequal hardness into juxtaposition, and lowlands will then be worn on the softer beds. To some extent this is the case in the Appalachian region, where trellised drainage is most notably developed. In regions of recent faulting, narrow fault blocks may be dropped, giving lowlands, or erosion may follow zones of crushed material along fault lines, etching out straight valleys pp. 191–192. In the typical fault topography of California, there is almost perfect dendritic drainage in the blocks between the faults. To bring out this feature clearly, contrast the Priest Valley and San Mateo (Cal.) sheets with the Vandiver (Ala.) and Monterey (Va.-W. Va.) sheets. In the two latter, the parallel valleys are closely spaced, the ridges are narrow, and transverse valleys and right-angled turns are common.

From what has been said above, it follows that one can tell something from the drainage pattern of a region regarding its structure, even though neither geological nor contour maps are available. For instance, in Fig. 7 *A*, the typical dendritic pattern

might suggest horizontal sedimentary rocks, massive igneous rocks, or a region of crystalline metamorphics, but it would be distinctly unsafe to conclude definitely, without further information, that the region was underlain by horizontal beds. On the other hand, a drainage pattern like that shown in Fig. 7 *B* may rather safely be interpreted as having been formed on a considerably tilted or folded group of alternating hard and soft strata. Of course, drainage patterns in glaciated regions commonly bear little or no relation to underlying rock structure.

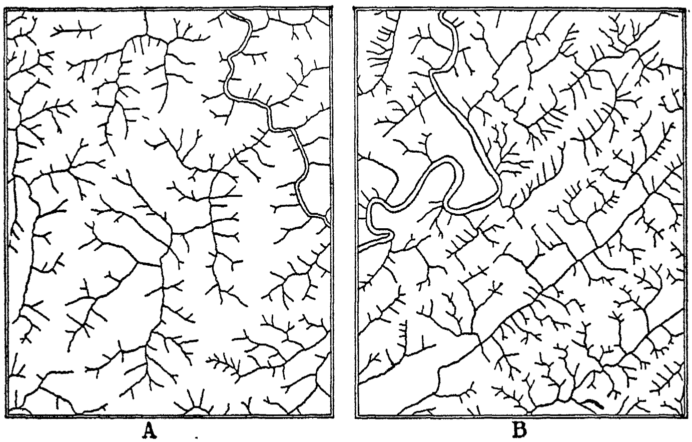


Fig. 7.—Dendritic (A) and trellised (B) drainage patterns traced from the Briceville (Tenn.) sheet. (*U. S. Geol. Survey.*)

Certain minor features of a drainage pattern are also of interest and importance in structural interpretation. For instance, considerable bends in a river may be only meanders, or may be related to structure. Initial consequent streams on a newly emerged surface (p. 101) will, of course, tend to pass around any domes present, as in that stage the domes are original topographic elevations. If the stream is antecedent to the dome (p. 102) which is uplifted so slowly that a valley is cut *pari passu* with the uplift, or if the stream is on a peneplaned surface across the top of a dome, and the structure consists of hard and soft rocks, the drainage line may cut through a soft layer onto the inclined

surface of a hard bed, where it will cut laterally more easily than downward, shifting down the dip to develop curves around the structure. On the other hand, if the rocks are of nearly equal resistance, the stream will probably intrench itself into the fold, without producing a curve.

There is usually no means on a topographic map of definitely identifying such curves in streams. Any pronounced bend in a stream that does not appear to be meandering, or any bend that is obviously not a meander, may suggest such an origin, but, of course, no such inference from the map should be accepted unless supported by other evidence, either on the map or in the field, because there is such a variety of conditions that can produce bends in streams.

If, however, several minor streams show parallel curves, the assumption of structural control becomes almost a certainty. Something approaching this condition occurs on the Quakerstown (Pa.) sheet. Detailed geological information is not at hand to determine whether this results from structural control, though it is highly probable that it does. A faint tendency toward such curved drainage lines near Lehigh on the Atoka (Okla.) sheet is known from the geological map (Folio 79) to be controlled by the end of a pitching syncline. The broad curve on the San Rafael River (San Rafael sheet, Utah) would not prove much, if it stood alone, but in conjunction with parallel curves of minor valleys (which do not show blue stream lines because of aridity), it is good evidence of the end of a pitching fold.

Another minor drainage feature of structural significance is the number and length of tributaries flowing into opposite sides of a longitudinal, or strike, river. The rocks on one side of such a stream dip toward the valley, and on the other, away from it. If the region is one of alternating resistant and non-resistant strata, such a stream will tend to shift down the dip (p. 106) making the valley asymmetrical (p. 155), one side being an escarpment resulting from sapping of softer layers under harder ones, the other a dip slope on the surface of a harder layer from which the softer has been stripped.

On the escarpment side of the valley, tributaries will be few, short, and steep, whereas on the dip-slope side they will be more numerous, longer, and gentler. On the Cooperstown (N. Y.) sheet, Schenevus Creek shows many long north-side tributaries, and very few and short ones on the south. On the Oneonta (N. Y.) sheet, this holds true for practically every stream that flows more nearly east or west than north or south. On both maps, the long tributaries are flowing down the dip, in a southerly direction.

The number, length, and perfection of the tributaries on the northeast side of Escalante River (Escalante sheet, Utah), contrasted with their poverty on the southwest side, is indicative of southwest dip. The same relationship along Dot Klish Canyon (Marsh Pass sheet, Ariz.) indicates southeast dip. Along Sand Draw (Blue Mesa sheet, Wyo.), practically all of the tributaries occur on the southwest side, flowing northeast in the direction of regional dip.

Exceptions to this principle may occur, as along the creek flowing southeast across secs. 5, 8, 9, and 15, T. 45 N., R. 96 W., on the Blue Mesa sheet, where the long tributaries appear to flow nearly opposite to the dip. This, in part at least, is explained by its proximity to Grass Creek, leaving no drainage area from which it could gather waters, on the up-dip side. Also, since this escarpment is several hundred feet high, and facing in a westerly direction, from which the rain-producing winds blow, its steep face may get more rainfall than the broad lowland to the southwest. Such exceptions are probably rare, and the principle enunciated in the foregoing paragraphs seems to be perfectly valid for use in map interpretation, keeping in mind, of course, that in few cases can interpretation from topographic maps result in absolute certainty regarding structure, unless a variety of corroborative evidence is found.

In homogeneous rocks there is an almost universal tendency for tributaries to join the trunk stream with the acute angle of junction above the tributary, its apex pointing downstream. This results from the fact that the tributaries, like the main

streams, are controlled by their immediate slope, which for each tributary is a resultant of the valley side for the main stream plus the initial slope of the area. Also the current of the main river may help to force the tributary mouth downstream.

In folded regions, however, in which the course of the master stream is diagonal to the main structure, tributaries working back on soft rocks may develop on one side with the acute angle downstream and on the other, upstream. On the Saypo (Mont.) sheet (S. cent. rect.), Big George, Mortimer, Blacktail, and Hanna gulches make acute angles with North Fork of Sun River on the downstream side, the apex of each pointing upstream. These abnormal junctions are, clearly, the result of structure. Folds, faults, or pronounced joint planes might control the courses of tributary streams, and result similarly in abnormal tributary angles. Other examples occur on the Rangley (Colo.) sheet, on the north side of White River, in secs. 1, 2, and 3, T. 1 N., R. 103 W.

Such abnormal junctions, or barbed tributaries, may also result from stream piracy (p. 107). Fine examples occur on the Todd Lakes (Mont.) sheet (N. ½ sec. 12, T. 31 N., R. 44 E.) and on the Hollow Springs (Tenn.) sheet (SW. ¼ N. cent. rect.) where the general topographic conditions clearly indicate piracy rather than structure.

Barbed tributaries on the Connell sheet (Wash.), on the east, side of a small stream flowing southwest across secs. 15 and 22., T. 12 N., R. 33 E., are too numerous to be entirely accidental. The relations do not suggest piracy as strongly as they do structural control. Numerous examples on the Walla Walla (Wash.) sheet also seem to be related to structure, for instance, in the SW. ¼ sec. 8, T. 11 N., R. 37 E.; near the center of sec. 17, T. 11 N., R. 37 E.; near the center of sec. 13, T. 11 N., R. 36 E.; one in the N. ½ sec. 16, T. 10 N., R. 38 E.; and several in the W. ½ sec. 2, T. 10 N., R. 36 E.

Still another minor relation of drainage pattern to structure is a tendency toward radial arrangement on domes. If the site of the dome is already crossed by a well-defined stream large

enough to hold its way as a true antecedent athwart the uplift, little or no radial drainage will develop. If no antecedent stream exists, a new uplift, such as a salt dome (Fig. 8.), will become a topographic high with radial drainage. If a dome is peneplaned

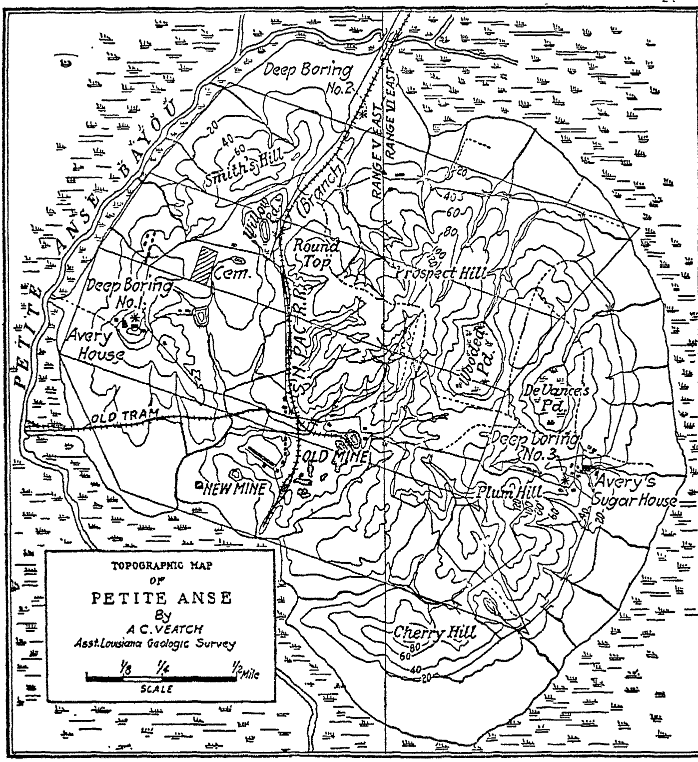


FIG. 8—A salt dome, showing topographic high, with radiating drainage. (Petite Anse.)

and buried under other beds, or is as deeply glaciated as the northern part of the Cincinnati arch, the streams may be largely superimposed, with little or no regard to structure.

On the other hand, any topographic high tends to have radiating drainage, as witness Mount Monadnock (Monadnock sheet, N. H.). Naturally, the more nearly the structure is identical

on all sides, as on a dome, the more nearly perfect will the radial arrangement be. The state map of Missouri shows a distinct tendency toward radial drainage on the Ozark dome. Radial drainage is especially perfect on some of the more notable volcanic cones (Marysville Buttes and vicinity, Cal.; Shasta special, Cal.; Mt. Hood, Ore.-Wash.; Crater Lake National Park, Ore.; Island of Kauai, Hawaii; and Waipio, Hawaii).

To sum up, radial drainage by no means always occurs on domes, is especially common on volcanic cones, and is known on eminences of other types. Although its presence in exceptional perfection may lead to a suspicion of folding, especially in regions known to be free from volcanic cones, no conclusions should be drawn without confirmatory evidence.

THE EFFECT OF THE STAGE OF THE EROSION CYCLE

Since structure is reflected in topography only when erosion has etched out the softer rock leaving the harder in relief, it is obvious that the structural record will be most striking in those stages of the cycle in which the relief is considerable, that is, from about middle youth to middle maturity. In early youth even the softer beds have not yet suffered much erosion to bring the harder into relief; and in late maturity even the harder rocks have usually begun to wear down appreciably, and the control exercised by the thinner or less extremely resistant of the hard beds will begin to be lost. In general, it is in late youth and early or middle maturity that the differences of hardness are most strikingly shown, and a large proportion of the maps used in the following pages represent regions in those stages of development.

REGIONAL ESCARPMENTS AND REGIONAL DIP

Maps

Fort Payne, Ala.-Ga.
Gadsden, Ala.
Fayetteville, Ark.-Mo.
Eureka Springs, Ark.-Mo.
Harrison, Ark.-Mo.
Marshall, Ark.
Winslow, Ark.-Okla.
Fort Collins, Colo.
Loveland, Colo.
Rangely, Colo.

Lawtey, Fla.
Macclenny, Fla.-Ga.
Everett City, Ga.
Folkston, Ga.-Fla.
Moniac, Ga.-Fla.
Renault, Ill.-Mo.
Eureka, Kan.
Fredonia, Kan.
Independence, Kan.
Leavenworth, Kan.-Mo.
Sedan, Kan.
Harrodsburg, Ky.
Louisville, Ky.
Monticello, Ky.
Princeton, Ky.
Providence, Ky.
Richmond, Ky.
Frostburg, Md.-W. Va.-Pa.
Laurel, Md.
Piedmont, Md.-W. Va.
Relay, Md.
Morton, Miss.
Crystal City, Mo.-Ill.
De Soto, Mo.
Springfield, Mo.
Weingarten, Mo.-Ill.
New Brunswick, N. J.
Sandy Hook, N. J.-N. Y.
Albany, N. Y.
Albion, N. Y.
Auburn, N. Y.
Baldwinsville, N. Y.
Berne, N. Y.
Brockport, N. Y.
Chittenango, N. Y.
Clyde, N. Y.
Dunkirk, N. Y.
Durham, N. Y.
Geneva, N. Y.
Kaaterskill, N. Y.
Lockport, N. Y.
Macedon, N. Y.
Medina, N. Y.
Niagara Falls, N. Y.
Oneida, N. Y.
Oswego, N. Y.
Palmyra, N. Y.
Rochester, N. Y.
Schoharie, N. Y.
Skaneateles, N. Y.
Slide Mountain, N. Y.
Syracuse, N. Y.
Tonawanda, N. Y.
Weedsport, N. Y.
Westfield, N. Y.
Bainbridge, Ohio.
Bucyrus, Ohio.
Chillicothe, Ohio.
Circleville, Ohio.
East Columbus, Ohio.
Greenfield, Ohio.
Marengo, Ohio.
Mount Gilead, Ohio.
Norwalk, Ohio.
Oberlin, Ohio.
Peebles, Ohio.
Roxabell, Ohio.
Sandusky, Ohio.
Vanceburg, Ohio.
Vermilion, Ohio.
Westerville, Ohio.
Claremore, Okla.
Hominy, Okla.
Kiefer, Okla.
Nowata, Okla.
Nuyaka, Okla.
Okmulgee, Okla.
Pawhuska, Okla.
Vinita, Okla.
Wewoka, Okla.
Altoona, Pa.
Bedford, Pa.
Bellefonte, Pa.
Ebensburg, Pa.
Philipsburg, Pa.
Briceville, Tenn.

Chattanooga, Tenn.
Kingston, Tenn.
Maynardville, Tenn.
Abilene, Tex.
Albany, Tex.
Eden, Tex.
Flatonia, Tex.
Gay Hill, Tex.
Navasota, Tex.
San Angelo, Tex.
Sweetwater, Tex.
Castlegate, Utah.
East Tavaputs, Utah.
Escalante, Utah.
Price River, Utah.
Sunnyside, Utah.
Wellington, Utah.
Kilmarnock, Va.
Davis, W. Va.-Md.
Elk Garden, W. Va.-Md.
Greenland Gap, W. Va.
Onega, W. Va.
Kendall, Wis.
Mauston, Wis.
Neshkoro, Wis.
Poynette, Wis.
Ripon, Wis.
Sparta, Wis.
The Dells, Wis.
Tomah, Wis.
Bald Mountain, Wyo.
Dayton, Wyo.
Fort McKinney, Wyo.
Meeteetse, Wyo.

With a gently inclined hard layer of rock capping a softer one, a line of cliffs or steep slopes will be developed (Fig. 9) which will retreat in the direction of dip by the process of *sapping*, the soft layer wearing back underneath the harder, which then caves down in blocks. Such a line of cliffs or steep slopes is termed an escarpment (p. 100). On the flanks of major uplifts, such as the Cincinnati arch or the Ozark dome, the low uniform inclination of the beds is spoken of as *regional dip*. An escarpment originating under such conditions is commonly termed a *regional escarpment*, and may be continuous for many miles, facing opposite to the dip. In traveling in the direction of dip, one climbs its steep slope or face and descends its gentler backslope.

Probably the most familiar example of such a feature is the famous Niagara escarpment in the state of New York, facing north, and indicating a gentle regional south dip. On the Niagara Falls quadrangle, its height is about 200 feet. It can be traced east across the Tonawanda and Lockport sheets as a very distinct feature, which must not be confused with the remarkably fine beach ridge a few miles to the north, followed by the "Ridge Road". In the extreme southeast corner of the Lockport sheet is a small section of another parallel escarpment

formed by the Onondaga limestone. Of course, the age and the exact character of these rocks were not learned from the contour maps, but the two parallel escarpments, both of which may be traced across the Medina sheet, next east, may reasonably be interpreted to mean: (1) alternating hard and soft stratified rocks, (2) dipping gently southward, so that (3) the southern escarpment is on younger rocks than the northern. Both escarpments can be traced across the next sheet east, the Albion,

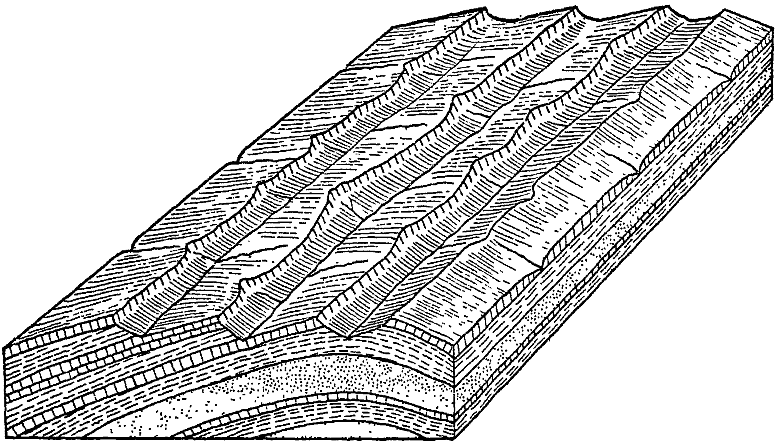


FIG. 9.—Block diagram showing relation of topographic features to dip of rock beds. (*Modified from Cox, Dake and Muilenburg.*)

though less distinctly; and on still the next, the Brockport, the Onondaga escarpment swings somewhat southward off the map, and the Niagara escarpment becomes much less regular and easy to recognize. Eastward across the Rochester, Macedon, Palmyra, Clyde, Weedsport, and Oswego sheets, the escarpment is almost completely lost in the deep glacial drift that constitutes the drumlin (p. 35) area of central New York.

The Onondaga escarpment shows up well on the Oneida and Chittenango sheets, but becomes fainter as it is traced westward across the Syracuse and Baldwinsville quadrangles, and on the

Skaneateles, Auburn, and Geneva sheets it becomes quite obscured in the deep drift of the drumlin area, although the belt of Onondaga crosses these sheets. The escarpment faces north, and indicates a regional dip to the south. The belt of Niagara also crosses the Oneida and Chittenango sheets, just south of Oneida Lake, but does not there produce the slightest hint of an escarpment, either because the escarpment maker becomes relatively less resistant, or because it is obscured by deep glacial drift.

Even more striking than the Niagara escarpment, and perhaps almost as well known, is the one that forms the east face of the Appalachian plateaus from New York to Alabama, quite generally spoken of as the Allegheny Front. In New York it is a continuation of escarpments striking east and west across the state on beds dipping southward from the uplifted pre-Cambrian or Canadian shield or oldland. As the dip changes in eastern New York, the escarpment, which has an east-west trace on south-dipping beds across the Schoharie sheet, swings to southeast on the Berne sheet, indicating southwest dips. In fact, there are two distinct escarpments. On the Albany sheet, the strike swings more nearly south, indicating that the dip has changed toward the west. Here it is known as the Helderberg escarpment. On the Durham sheet is still a third escarpment trending southeastward. As the beds are traced southeast, the dip increases somewhat, and the tendency to separate escarpments becomes less distinct. On the Kaaterskill and Slide Mountain (N. Y.) sheets the major escarpment swings to a southwesterly strike, indicating a change of regional dip to northwesterly. In this section it is the east face of the Catskills.

Across Pennsylvania, it is best shown on the Bellefonte, Philipsburg, Altoona, Ebensburg, and Bedford sheets, the strike changing from N. 45° E. on the Philipsburg to about N. 20° E. on the Bedford, as a result of a corresponding change in the direction of the regional strike and dip of the rocks. In Maryland, it is shown on the Frostburg sheet, in West Virginia on the

Piedmont, or in more detail on the larger-scale Elk Garden, Greenland Gap, Davis, and Onego quadrangles. Across Tennessee, where the same feature is called the Cumberland escarpment, it is well exhibited on the Maynardville, Briceville, Kingston, and Chattanooga maps. In Alabama, it is shown on the Gadsden and Fort Payne sheets, the latter showing much greater detail than the former.

There are places along this escarpment, between New York and Alabama, where, as a result of faulting or minor folding, it practically loses its identity, but most of the way it is a distinctive feature of the topography, striking northeast and southwest, facing southeast, and indicating northwest regional dip off the Appalachian uplift into the structural trough between it and the Cincinnati and Nashville domes.

Another great regional escarpment is the famous Book Cliffs of Utah and Colorado, which may be traced across the Price River and East Tavaputs (Utah) sheets for over 100 miles. These are old sheets on the scale of $1/250{,}000$ and with a 250-foot interval. A portion of the escarpment is shown in much greater detail on the Castlegate, Wellington, and Sunnyside quadrangles. On the Castlegate, the regional dip is nearly straight north, and in conformity therewith the escarpment strikes east-west and faces south. On the Sunnyside sheet the dip shifts to northeast, and the escarpment accordingly strikes northwest-southeast, and faces southwest. Other changes in trend occur in response to structural variations. This is probably the greatest regional escarpment in the United States, if not in the world, and is only rivaled by some of the fault or fault-line scarps of the first magnitude. It is a distinctive feature of the topography for several hundred miles, and is 2,000 to 3,000 feet in height throughout considerable distances.

The coastal plain, with its uniform dip of strata toward the sea, would be a favorable region for the development of continuous regional escarpments, were there sufficient differences in hardness of the formations to produce the requisite etching out of softer beds. Hints of such escarpments facing the interior are

recognizable on a few coastal-plain maps. The line of hills from Navesink Highlands (Sandy Hook sheet, N. J.-N. Y.) west and southwest across the New Brunswick (N. J.) sheet is well known, and by dint of considerable imagination it can be followed across other sheets to the south and west, where it is somewhat obscured by poor mapping.

A faint suggestion of such relations exists in the lowland followed by the Washington and Baltimore road across the Laurel and Relay (Md.) sheets, at the inner edge of the coasta plain. Many of the streams to the northwest of it occupy gorges, whereas to the southeast they have broad valleys. Although the lowland is a continuous feature, it is not occupied by any single river, but is obviously the result of a softer layer of coastal-plain material partially stripped away. As an escarpment, however, the feature is very obscure.

Southern Alabama is usually cited as our most striking example of a belted plain, crossed by successive regional escarpments. Unfortunately, however, no good maps are available of this section. In Mississippi, the ragged edge of a north-facing escarpment, indicating south dip, crosses the Morton sheet.

A moderately pronounced escarpment, striking northeast-southwest, and facing northwest in conformity with the southeast regional dip of the Texas coastal plain, passes through Flatonia (Flatonia sheet), and is fairly distinct on the Gay Hill and Navasota sheets.

Regional escarpments facing inward toward the center of the uplift are likely to be formed about the borders of domes from which the rocks dip outward in all directions, but only if there are sufficient differences of rock hardness to allow the beds to be etched into relief. The Cincinnati arch is perhaps as well known and thoroughly mapped as any such dome, and affords a good illustration of the behavior of such escarpments.

Northward from the Ohio River, an escarpment shows very plainly on the Vanceburg, Peebles, Bainbridge, Greenfield, Roxabell, Chillicothe, Circleville, East Columbus, Westerville, Marengo, and Mount Gilead (Ohio) sheets. At this point it

begins to swing eastward, and across the Bucyrus and Norwalk (Ohio) quadrangles is practically lost as a result of glaciation. It cuts across the southeast corner of the Sandusky (Ohio) sheet, the swing to the east becoming much more pronounced.

From the Vanceburg to the Chillicothe sheets the strike is northeast, and the escarpment faces northwest in response to southeast regional dip. From the Circleville to the Mount Gilead sheets the regional dip has changed to nearly straight east, and the escarpment in response strikes north-south and faces west. Farther north, it swings to the east as a result of southerly dip off the Canadian oldland.

A large part of the Cincinnati arch lies in Kentucky. In that state, however, there are fewer and poorer available maps. Nevertheless, the same escarpment may be clearly distinguished. On the Richmond sheet, it strikes more nearly east-west, facing in a northerly direction, an indication of more southerly dip on the south side of the dome. A small bit of the escarpment shows in the southwest corner of the Harrodsburg sheet, where it strikes nearly east-west, facing north in response to south dip. On the Louisville quadrangle a fragment of the escarpment in the southwest corner faces nearly east, indicating that the regional dip has changed to the west, on the west flank of the dome. The Monticello sheet shows another striking escarpment on a younger and higher formation on the southeast flank of the dome. In response to southeast dip, the escarpment strikes northeast-southwest, and faces northwest.

Unfortunately, maps are not available in Indiana to show the west side of the structure.

The uplift of central Wisconsin is fringed by an inward-facing escarpment, very pronounced on the west and south, but nearly obliterated on the east by heavy glaciation. Beginning with the extreme northeast corner of the Sparta quadrangle, the escarpment bears a general east and southeast course across the Tomah, Kendall, Mauston, and The Dells sheets, facing northeast and indicating southwest regional dip. On the east flank of the uplift, the Poynette, Neshkoro, and Ripon sheets, which

are crossed by the same formations, show scarcely a trace of escarpment, chiefly because of intense glaciation.

The Ozark dome has attracted much attention because of its relation to the great Mid-Continent oil fields on its west flank. Unfortunately, few good maps are available, showing its regional escarpments. One of the best is the Kiefer (Okla.), on which the escarpment has a trace of about N. 20° E., facing eastward, and indicating a regional dip slightly north of west, in conformity with its position on the west flank of the Ozarks. This same escarpment can be traced north across the east edge of the Hominy (Okla.) sheet, on which the smaller scale and larger interval employed tend to obscure its importance. Still farther north it can be followed along the boundary between the Nowata and Pawhuska (Okla.) sheets to the Kansas line. South from the Kiefer sheet, the same feature may be traced entirely across the east edge of the Nuyaka (Okla.) quadrangle, and it is presumably the same one that shows on the east portion of the Wewoka (Okla.) sheet.

West of this escarpment, and therefore on younger beds, is another on the Hominy and Pawhuska sheets, extending from south of Hominy to Pawhuska, and thence slightly northeast into T. 28 N., R. 10 E. Although inconspicuous on the map, in the field it is a very striking feature of the landscape.

On the Wewoka sheet are other escarpments, inconspicuous on this map with its large interval and small scale, which are doubtless prominent in the field and would show up well on a more detailed sheet. Such a one occurs at numerous points in R. 10 E., another in Tps. 9 and 10 N., R. 9 E., and still another in Tps. 9 and 10 N., R. 8 E.

Farther east and on older beds are good escarpments on the Claremore (Okla.) sheet, one extending from Broken Arrow north past Catoosa and off the north edge of the map in R. 16 E.; another from the east edge of T. 18 N., R. 15 E., northeast past Claremore to the vicinity of Fovil; and still another in Tps. 25, 26, and 27 N., R. 15 E. The westernmost of these extends north into the Nowata sheet, on the west side of the Verdigris River.

Several good escarpments also occur on the Okmulgee and Vinita (Okla.) sheets, all of which face in a general easterly direction and indicate regional dips to the westward.

The Independence (Kan.) quadrangle, directly north of the Nowata (Okla.) sheet, illustrates the contrast produced by change of interval. Escarpments that are barely discernible on the Nowata sheet (50-foot interval) are very striking on the Independence (20-foot interval), though both maps are on the same scale. Anyone who has access to an old edition of the Independence sheet (1894) should compare it with the present edition in order to understand why few of the Kansas maps show escarpments. The poor mapping is strikingly shown by a comparison of the area near Crane (cent. rect.) on the two sheets. A prominent escarpment over 100 feet high was completely ignored in making the earlier map, the omission of which cannot be blamed on the large interval. Although the Independence sheet shows very good escarpments at its north border, the next sheet northward, the Fredonia, does not give even the faintest hint of such features—of course, because of the poor mapping.

One of the most notable escarpments in Kansas, known as the Flint Hills, is very inadequately represented along the west border of the Sedan and Eureka sheets. It strikes east of north, faces slightly south of east, and results from a dip a little north of west.

On the south side of the Ozarks, in Arkansas, really good maps are also wanting. A north-facing escarpment occurs along the boundary of the Fayetteville and Winslow quadrangles. Another can be traced across the northeast portion of the Eureka Springs sheet, and becomes a striking feature across the Harrison and Marshall quadrangles. Although it is distinctly irregular, it faces, in general, slightly east of north, and results from south to southwest regional dip.

The most prominent physiographic feature in southwest Missouri is the Burlington escarpment, which crosses the northeast portion of the Springfield sheet, but the mapping is so poorly done that the escarpment is not recognizable. No good map of this feature is available.

On the east flank of the dome, the so-called Crystal or St. Peter escarpment shows on the De Soto (Mo.) sheet, between Pacific and Goldman, but is less obvious on the map than in the field. The same feature can be traced, but with some difficulty, across the Crystal City (Mo.-Ill.) sheet, along the line between Genevieve and Rush Tower School, thence to Concord School and off the map. Bloomsdale, on the Renault (Ill.-Mo.) sheet, is on the escarpment; and on the Weingarten (Mo.-Ill.) sheet it lies east of a line drawn from Zell to River Aux Vases, and thence to Independence School. It faces southwest, and results from northeast regional dip. On this flank of the dome, dips are actually steeper than those in Oklahoma, the lack of perfection of the escarpments resulting from the less difference in resistance to erosion exhibited by the formations here than in Oklahoma.

Even as far east as the western tip of Kentucky, the effects of the Ozark uplift are felt in regional escarpments. A distinct but very irregular one may be traced across the Princeton sheet, almost through Princeton, and another less distinct but more regular approximately from Rufus to Claxton. On the Providence sheet a very prominent one may be traced from Sullivan to Yarbro, and suggestions of others occur near Newhope Church (SE. rect.) and near Sugargrove School (W. cent. rect.). This area is known to be complicated by faulting; nevertheless the regional escarpments, all of which face in a general southwest direction, indicate northeast regional dip off the Ozark dome.

Smaller domes not infrequently exhibit the same phenomenon of inward-facing circular escarpments corresponding to outward dips. This is very well exhibited on the Davis (W. Va.-Md.) sheet, at Canaan Valley; on the Meeteetse (Wyo.) sheet, at Little Buffalo Basin and again at Spring Creek Basin; on the Escalante (Utah) sheet, at Circle Cliffs; and on the Rangely (Colo.) sheet, at Raven Park.

The central region of Texas affords an especially interesting example of two sets of escarpments related to different structures in a single region. The Paleozoic rocks dip nearly west as a result of broad regional uplifts from the Wichitas to the Llano-

Burnett region. This is reflected in regional escarpments trending nearly north-south, and facing east, two of which show plainly on the Albany sheet. The Cretaceous, which overlies the Paleozoic with slight discordance, here has a general south dip toward the coastal-plain area, clearly reflected in east-west north-facing escarpments across the Abilene, Sweetwater, Eden, and San Angelo sheets.

A complication in interpreting escarpments may sometimes be encountered in areas like the Loveland and Fort Collins (Colo.) sheets. Here at first glance there appears to be one enormous escarpment facing east over the Great Plains, and there might be a tendency among beginners to infer a west regional dip. Closer examination, however, suggests that the long parallel ridges represent upturned edges of more resistant rocks, from among which the less resistant have been etched. The upland on the west does not exhibit this type of topography at all, and the nearly dendritic drainage suggests more massive rocks. The inference at once becomes strong that the sediments in the "hogbacks" are dipping eastward away from the massive rocks of a mountain core. Still closer examination of the "hogbacks" reveals that most of them have their steep slope facing west, suggesting east dip and confirming the above inference (however, compare with pp. 152–154).

On the Bald Mountain (Wyo.) sheet the situation is similar. The great upland consists of more massive rocks which constitute the core of the range, and the southwest-facing escarpment does not mean northeast dips, but results from a harder core flanked by softer rocks. On the southwest side of this core the rocks dip southwest, not northeast, and a faint suggestion of this is given by the bits of northeast-facing minor escarpment in secs. 30 and 31, T. 53 N., R. 90 W., and diagonally across T. 54 N., R. 92 W. These fragments of escarpment would doubtless show as very definite and practically continuous features, if mapped on a larger scale, with a 20-foot or even a 50-foot interval. The northeast-facing escarpment on the Fort McKinney (Wyo.) quadrangle, continuing across the Dayton (Wyo.) sheet, is

another illustration, this time on the northeast flank of the Bighorns, of the same type of structure.

Other and quite different features may, under certain conditions, closely simulate regional escarpments resulting from structure. Among these, lake and marine terraces and wave-cut cliffs are rather common (pp. 53–59). On the Kilmarnock (Va.) sheet is such a marine wave-cut cliff facing east. The fact that it faces Chesapeake Bay, and that there is striking topographic unconformity (p. 55), are distinguishing features. The regional dip is southeast and the escarpment is in no way related to structure. A similar feature occurs on the Everett City (Ga.) sheet, and an even higher and more striking one on the Folkston, Moniac, Macclenny, and Lawtey sheets of Georgia and Florida. In a coastal-plain area, regional dip is usually toward the sea, and this fact is helpful in avoiding misinterpretations.

Along the Great Lakes are also many abandoned shore lines which might be mistaken for regional escarpments. North Ridge, Middle Ridge, and Butternut Ridge on the Oberlin (Ohio) sheet represent such wave-cut benches. In this area, however, the regional dip (as shown on geological maps) is to the south, so that the wave-cut cliffs face in the same direction as the regional escarpments might be expected to do. It seems rather probable that the line of cliffs across the Vermilion (Ohio) sheet are the result of regional dip, and on the Westfield and Dunkirk (N. Y.) sheets the upper bench is almost certainly structural, though traces of low wave-cut cliffs occur between it and the lake.

In general, wave-cut terraces face existing bodies of water, either lakes or seas, or at least border plains that are, obviously, very youthful. Of course, it is true that structural escarpments, as shown above, may also face such water bodies. One should, then, be very cautious in interpreting escarpments so situated; but, if all traces of such bodies, former or existing, are absent, there will usually be small possibility of wave-cut benches.

Cliffs bordering flood plains are another feature that beginners are likely to confuse with structural escarpments. For instance, on the Leavenworth (Kan.-Mo.) sheet, both sides of the Missouri River are flanked with notably regular lines of cliffs. However, since they face in opposite directions, and are about equally developed, they are, obviously, not related to regional dip, and are not true *regional* escarpments. The regional dip here is actually to the northwest. Equally striking are similar features along the Mississippi River on the Renault (Ill.-Mo.) sheet, where the regional dip is northeast. They are about equally developed on both sides of the river, one facing in the direction of regional dip, and one in the opposite direction. They are, obviously, not regional escarpments developed in response to structure. There is, however, a regional escarpment on this sheet, striking northwest-southeast, and facing southwest, best exhibited at Bloomsdale in the southwest corner of the map.

Additional maps illustrating regional escarpments

Brownsville, Ky.
MammothCave, Ky.
Little Muddy, Ky.
Booneville, N. Y.
Brier Hill, N. Y.
Carthage, N. Y.
Hammond, N. Y.
Ogdensburg, N. Y.
Port Leyden, N. Y.
Belle Fourche, S. D.
Deadwood, S. D.
Edgemont, S. D.-Neb.
Harney Peak, S. D.
Hermosa, S. D.
Oelrichs, S. D.-Neb.
Rapid, S. D.
Redwater, S. D.
St. Onge, S. D.
Franklin, Tenn.
Hollow Springs, Tenn.
McMinnville, Tenn.
Murfreesboro, Tenn.
Nashville, Tenn.
Pikeville, Tenn.
Standingstone, Tenn.
Wartburg, Tenn.
Woodbury, Tenn.
Aladdin, Wyo.-S. D.-Mont.
Devils Tower, Wyo.
Newcastle, Wyo.-S. D.
Sundance, Wyo.

THE SIGNIFICANCE OF THE ASYMMETRICAL RIDGE

Maps

Elmoro, Colo.
Jesup, Ga.
Independence, Kan.
Lockport, Ky.
Pawpaw, Md.-W. Va.-Pa.
Piedmont, Md.-W. Va.
Plainfield, N. J.-N. Y.
Somerville, N. J.
Wingate, N. M.
Cooperstown, N. Y.
Kaaterskill, N. Y.
Oneonta, N. Y.
Weedsport, N. Y.
Kinston, N. C.
Williamston, N. C.
Winterville, N. C.
Winton, N. C.
Kreenfield, Ohio.
Hiefer, Okla.
Garrisburg, Pa.
Hollidaysburg, Pa.
Lykens, Pa.
Allendale, S. C.
Ellenton, S. C.-Ga.
Shirley, S. C.
Hollow Springs, Tenn.
Albany, Tex.
Tascotal Mesa, Tex.
Escalante, Utah.
Wellington, Utah.
Connell, Wash.
Walla Walla, Wash.
Wallula, Wash.
Greenland Gap, W. Va.
Wardensville, W. Va.-Va.
Kendall, Wis.
Cloud Peak, Wyo.
Grass Creek Basin, Wyo.
Hanna, Wyo.
Newcastle, Wyo.-S. D.
Sheridan, Wyo.-Mont.

If a harder layer of rock above a softer stratum is dipping slightly but appreciably, there results an asymmetrical ridge, the steeper side of which is an escarpment produced by sapping (p. 137), and the gentler slope of which, commonly termed a dip slope, inclines in the opposite direction (Figs. 9 and 10). To the extent that the bed above is softer than the resistant layer, it will be stripped off, leaving a true dip slope actually controlled by and coinciding with the inclined surface of the harder bed. Such an asymmetrical ridge is termed a *cuesta.* Bandera Mesa and Tascotal Mesa (Tascotal Mesa sheet, Tex.) are especially good examples of this topographic form.

Streams crossing a cuesta may dissect it into a series of triangular hills, known locally as *flatirons.* Ed Point in the central rectangle of the Cloud Peak (Wyo.) sheet is a good example

The dip responsible for many regional escarpments is so slight that the ridge does not appear to be asymmetrical. This is seen

on the Kendall (Wis.) sheet, the ridge tops near the escarpment (secs. 34, 35, and 36, T. 17 N., R. 1 W.) rising to a maximum of about 1,440 feet, and reaching to 1,400 feet (sec. 19, T. 15 N., R. 1 E.) some 10 miles farther south. The upland, therefore, does not slope perceptibly away from the escarpment, unless

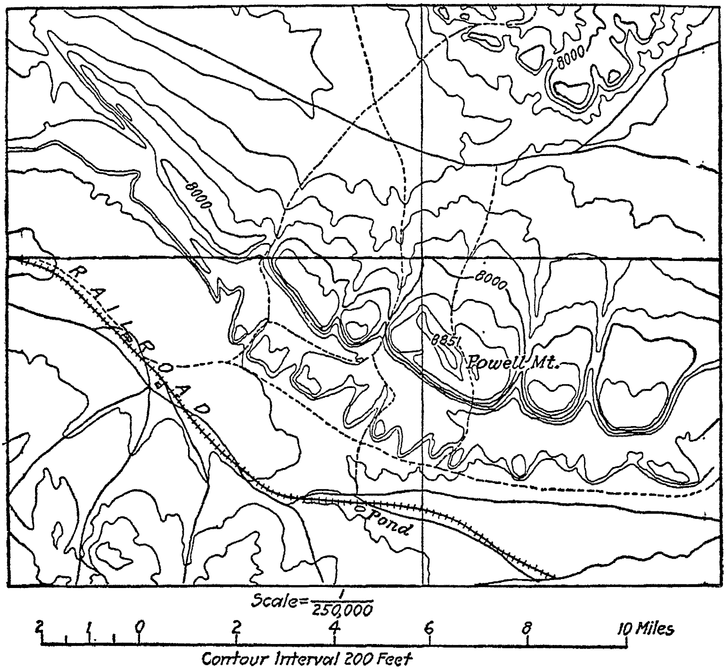


FIG. 10.—Topographic map showing cuesta with dip and escarpment slopes (Wingate sheet, New Mexico, *U. S. Geol. Survey.*)

long distances are taken into consideration. On the Greenfield (Ohio) sheet the upland remnants southeast of the escarpment do not decline appreciably in a distance of 4 miles. On the Hollow Springs (Tenn.) sheet, the decline of the plateau southeast in the direction of dip is very slight, though perceptible, not averaging more than 10 or 15 feet to the mile. While such features are sometimes termed cuestas, the name is more com-

monly applied to ridges the backslope of which is distinctly perceptible, but also distinctly less than that of the escarpment slope. A series of three typical cuestas occurs on the east half of the Wingate (N. M.) sheet, between the railroad and Hosta Butte to the north (Fig. 10).

The lower limit of dip which will permit of a recognizable backslope depends on the completeness with which the overlying soft bed is stripped from the hard layer, and this, in turn, is partly dependent on the contrast in resistance between the two beds. The greater the contrast the more perfect the stripping, and the more complete the reflection of structure in topography. Rarely will a dip much under half a degree give a recognizable dip slope, whereas a degree or more will usually do so.

On the Independence (Kan.) sheet, the escarpments in T. 31 S., R. 15 E. have an easily discernible dip slope with a dip averaging slightly under a half degree. On the Albany (Tex.) sheet there are three distinct escarpments from Albany to the west side of the map. Of these, the easternmost and westernmost show very perceptible backslopes. The back area of the intermediate one is so limited that its slope is not easily estimated. In this area the regional dip does not average much over 50 feet to the mile.

On the upland of the Kaaterskill (N. Y.) sheet, the dissection has been so complete that the original direction of slope is not obvious. The fact that the main drainage of the upland heads near the escarpment, and flows away from it rather than over its face, is probably an indication of the slope before dissection was so far advanced.

With steeper dips, the backslope is usually much more obvious, as at Powell Mountain (Fig. 10) in the east central portion of the Wingate (N. M.) sheet, or on the Kaiparowitz Plateau, on the Escalante (Utah) sheet. The distinction between backslope and escarpment becomes less striking with increasing dip, until on many of the Appalachian ridges, both slopes are essentially equal (Harrisburg, Lykens, and Hollidays-

burg sheets, Pa.). With dips of over 35°, the asymmetry of the ridge is often largely lost in talus accumulation, and not often can it be used to indicate the direction of inclination of the beds.

With high dips, the backslope, if completely stripped, may become the steeper of the two, especially if the bed above the hard layer is much softer than the bed below it, or if the underlying soft bed is much thinner than the one above, so that the escarpment face is less perfectly developed than the dip slope.

On the northeast flank of Grass Creek Basin (Grass Creek Basin sheet, Wyo.), for example, the escarpment faces southwest over a lowland as it normally should, with a definite backslope to the northeast. On the other hand, between Coalmine Draw (SW. cor. N. cent. rect.) and the main fold is a ridge the steep southwest slope of which would commonly suggest northeast dip. The published descriptions of this fold (*Wyo. Geol. Survey, Bull.* 11), however, refer to steep southwest dips on this flank, and make no mention of overturned beds.

On the same sheet, beginning an inch south of the east end of the fiftieth parallel, is an escarpment facing south over a lowland in normal manner, with backslopes to the north. It can be traced west to Wagonhound Spring (SW. rect.) where it turns abruptly southeast, and on the knob marked 6,230 faces northeast, with a southwest backslope. However, in secs. 19 and 20, T. 44 N., R. 98 W., the steep slope is southwest, which would normally suggest northeast dips. Inasmuch as such dips are not in harmony with the anticlinal structure, the anomaly might result from overturning of the beds, from faulting, or from steep dips, as explained above. Information on the point is not available.

Short Mountain (Wardensville sheet, W. Va.-Va.), the two limbs of which are separated by Meadow Run, is clearly a fold. The steeper slope of both ridges to the southeast might suggest overturning of one flank. Information furnished by the West Virginia Geological Survey,[1] however, is to the effect that the fold is a syncline, and not overturned. It seems, therefore, to be another case illustrating dips so steep that the backslope

[1] Written communication.

exceeds the escarpment slope, giving an incorrect idea of structure. Still another case seems to be Warm Springs Ridge (SE. rect., Pawpaw sheet, Md.-W. Va.-Pa.), which suggests west dip, whereas the geologic sheet indicates east dips ranging in this instance as low as 25 to 30°.

With steep dips, ridges normally show both slopes about equal (Harrisburg sheet, Pa.), and afford very little suggestion from which one would attempt structural interpretation. Sometimes, however, cliffs marking the outcrop of a resistant stratum may, if properly dissected, furnish a clue to structure where other evidence is indecisive. The Greenland Gap (W. Va.) sheet affords an excellent illustration. The numerous parallel ridges clearly indicate strong folding trending about N. 20° E., but, except in Allegheny Front, where there is conclusive evidence of northwest dip, the asymmetry of ridges is so poorly developed that the nature of the folds is not determinable by that criterion. Across New Creek Mountain, however, is a remarkable series of water gaps (Greenland, Cosner, and Kline), all of which are flanked on either side by peculiar curving cliffs. In the central part of the gaps the cliffs stand high above the streams, but toward either end decline to the valley bottoms, and disappear. The hard layer which they represent must, therefore, form an anticline. According to the geologic map (Piedmont folio No. 28), New Creek Mountain occupies the crest of this arch, in which the cliff-making Tuscarora quartzite overlies a series of softer shales.

In Knobly Mountain are equally interesting and suggestive cliffs at Robinson and Real Gaps (SW. rect.). There, however, *they occupy only one end of the gap*, forming an open "V" with the apex downstream. Evidently, then, this mountain is not an anticlinal crest, but only the southeast flank of the larger structure, the cliffs clearly indicating southeast dips. The lack of similar cliffs along Walker Ridge cannot be explained satisfactorily from the map.

On the older maps, the detail of cliffs has usually been omitted (*cf.* the Piedmont and Greenland Gap topographic sheets), but

with the increasing accuracy of the more recent work this criterion is likely to prove serviceable in numerous cases.

Rarely does the dip slope exceed that of the escarpment, and then only when both are fairly steep, so that, when a ridge shows one very steep slope and one that is rather gentle, little danger in interpreting the direction of dip is likely. On the whole, dips between 2 and 30° are likely with alternating hard and soft rocks to result in distinctly asymmetrical ridges, the gentle slope of which is in the direction of dip. Although asymmetrical ridges may result from other causes, such as the scouring of rock hills by an ice sheet, or from the building up of glacial drift into drumlins (Weedsport sheet, N. Y.), such hills are usually very irrgeular in distribution, whereas the asymmetrical hills that result from dipping beds are distinctly more regular and linear. The hills within the necks of intrenched meanders (Lecompte Bottom, Lockport sheet, Ky.) may frequently be asymmetrical, but are not to be interpreted as indicating structure.

Distinctly asymmetrical ridges, especially if they are linear and the gentle slope is very smooth and regular, constitute an almost unfailing indication of the direction of rock dip. Of course, the dip may be initial, as in the gravel layers that constitute the extensive alluvial fan at the base of Book Cliffs (Wellington sheet, Utah). In this area the regional dip is north, as indicated by the south-facing Book Cliffs escarpment, the backslope of which is best seen at Emma Park (NW. rect.). In sec. 9, T. 14 S., R. 11 E., however, is a flatiron ridge with a northwest-facing escarpment and a very definite backslope to the southeast. This is known to be a bit of dissected alluvial fan,[1] in which the initial dip is away from the main escarpment, corresponding to a surface of accumulation on the fan.

Not only do regular asymmetrical ridges indicate direction of dip; they also imply alternating hard and soft layers of stratified rock. The hard layer may, in some cases, be igneous, either lava flow or sill, but the topographic effect will be the same as though it were an equally resistant sedimentary layer,

[1] Personal communication from Professor Josiah Bridge.

and no method is known whereby the two can be distinguished on topographic maps. Examples of igneous rocks producing cuesta effects are not hard to find. Perhaps as striking as any examples to which reference can be made are First and Second Watchung Mountains on the Somerville (N. J.) and Plainfield (N. J.-N. Y.) sheets. On both, the escarpments and the dip slopes are clearly distinguishable, and the direction of dip unmistakably indicated. On the Elmoro (Colo.) sheet, the faint backslope to Raton Mesa suggests slight south dip. The resistant cap in this case is lava.

In a region consisting of a number of parallel, rather closely spaced escarpments, all facing in one direction, there is a marked tendency for the soft rock belts to become the sites of subsequent valleys (p. 101). Each valley is made up of a dip slope of one cuesta and an escarpment slope of the next, and is distinctly asymmetrical in cross-section. The asymmetry is coupled with a greater development of tributaries on the gentle or dip-slope side of the main valley (p. 131). On the Oneonta (N. Y.) sheet, all the valleys trending more nearly east-west than north-south have much steeper south than north walls, with the north-side or dip-slope tributaries much more strongly developed than those on the south, each east-west divide being essentially a cuesta with its escarpment facing north, the valleys occupying the intervening lowlands. The same condition obtains along Schenevus Creek, on the Cooperstown (N. Y.) sheet. The evidence on these sheets seems perfectly conclusive that there is a distinct southerly dip.

In the northeast corner of the Hanna (Wyo.) sheet, the main stream flows northeast. Many small tributary valleys show steep north walls, their south slopes being more gentle. Each divide may be looked upon as a cuesta with a southwest-facing escarpment, and the evidence for northeast dip is quite conclusive. On the Newcastle (Wyo.-S. D.) sheet most of the strike valleys in the northeast part of the map show steep west and gentle east sides, that is, the divides again consist of cuestas with northeast-facing escarpments, indicating southwest dips.

On the Sheridan (Wyo.-Mont) sheet the structure is less obvious. That the rocks are at least slightly tilted, and many of the smaller valleys subsequent on softer layers, is clearly evidenced by the parallel arrangement of streams. In T. 57 N., R. 82 W., the asymmetry of valleys and divides is conspicuous, the escarpments facing southwest in conformity to northeast dip. Similar conditions prevail in sec. 2, T. 55 N., R. 82 W.; in secs. 12 and 13, T. 55 N., R. 81 W.; in secs. 20 and 21, T. 55 N., R. 80 W.; and at other points. Enough reversals of this asymmetry are found, however, to suggest minor folding—as, for example, the northeast-facing escarpment in sec. 31, T. 54 N., R. 81 W. and its continuation in secs. 4 and 5, T. 53 N., R. 81 W.; also the one in secs. 21, 22, and 27, T. 53 N., R. 83 W. Although not proof of reversals of regional dip, these are sufficiently striking to demand further investigation. Unfortunately, available geological maps are not sufficiently detailed for confirmation.

On the Walla Walla, Connel, and Wallula (Wash.) sheets, the parallel arrangement of tributary valleys indicates a regional northeast-southwest strike, and there is a distinct tendency for the valleys and intervening divides to be asymmetrical, with escarpments facing southeast. The smallest tributaries of the subsequent strike valleys enter chiefly from the dip-slope side (W. ½ T. 8 N., R. 35 E.). Though no definite information seems to be available regarding the structure on these sheets, their position with respect to the Blue Mountains is consistent with regional northwest dip, suggested in the above-described topographic features.

With very gentle dips, and fairly thick non-resistant beds, the strike valleys may be wide, though still likely to preserve their asymmetrical character. On the Kiefer (Okla.) sheet, that part of Polecat Creek from Picket Prairie northeast is essentially a strike valley, and is characteristically asymmetrical, its gently inclined east side being the back or dip slope from the escarpment at Kiefer, whereas its steep west side is the next east-facing escarpment. The valley followed by the Oklahoma City branch of the St. Louis and San Francisco Railroad (NW. rect.), a part

of which is occupied by Little Polecat Creek, bears the same relation to structure. The valley of Browns Creek (SW. rect.) shows the same asymmetry.

There are, however, conditions which may, in certain regions, partially vitiate the criterion of asymmetrical valleys. According to Ferrel's law, moving bodies in the northern hemisphere are deflected to the right, and considerable attention has been directed to the possible influence of this deflection on lateral cutting by streams, and on the consequent lack of symmetry of certain valleys.[1]

In order to test the matter, many of the available coastal-plain maps of large scale and small interval, particularly the more recent and detailed ones, were assembled into blocks of sheets, and the symmetry of the valleys carefully noted. One block comprising forty-seven quadrangles in South Carolina and Georgia yielded the following results: Of the 47 sheets, 11 show practically no asymmetry of the valleys in either direction; 15 show streams with the east (left) bank slightly steeper, but only 4 of these are notably asymmetrical. On the other hand, 21 of the 47 show the west (right) bank the steeper, and 12 of these illustrate notable cases of asymmetry. Another group comprising 46 quadrangles in Virginia and North Carolina gave somewhat similar results. Of the 46 sheets, 25 show almost no asymmetry of valleys; 7 show streams with the east (left) bank slightly steeper, but only 1 of the 7 shows this to any remarkable degree. On the other hand, 14 of the 46 show valleys with the west (right) bank the steeper, and 8 of these contain notable examples of asymmetry. For illustration, see the following sheets: Kinston (N. C.), Williamston (N. C.), Winterville (N. C.), Winton (N. C.), Shirley (S. C.), Ellentown (S. C.-Ga.), and Jesup (Ga.).

In this area of southeast regional dips, structure should develop asymmetry with the southeast side of the streams the steeper.

[1] Lewis, E., *Am. Jour. Sci.*, 3d ser., vol. 13, 1887. Gilbert, G. K., *Am. Jour. Sci.*, 3d ser., vol. 27, p. 427. Davis, W. M., *Science*, n.s., vol. 27, pp. 31–33, 1908. Eakin, H. M., *Jour. Geol.*, vol. 18, pp. 435–447, 1910.

There is, however, a distinct tendency for the west or southwest (right) bank to be the steeper in the average case, in spite of opposing structure.

On several of the sheets, it is true, the larger streams are nearly at right angles to the strike, and should, therefore, show perfect balance in structural control; any asymmetry that results on these cannot be assigned to that cause. Some, however, are strike or nearly so, and these should show any influence that the structure of the region might exert. Both strike and dip streams show asymmetry, and more cases occur of the right bank steeper than the left. There are exceptions, as, for instance, the valley of Lower Three Runs, on the Allendale (S. C.) sheet, which has the left bank the steeper. Of course, the local development of a hard layer might easily reflect structure that would not show elsewhere. These cases certainly suggest that in coastal-plain areas of but slightly consolidated sediments the earth's rotation may be a stronger influence than regional dip in determining the asymmetry of valleys. It is certain, however, that in areas where the rocks are completely indurated, the asymmetry is largely the result of rock structure, and may be depended upon for important aid in interpreting structural conditions.

LACK OF RIDGE SYMMETRY AND AMOUNT OF DIP

Maps

Apishapa, Colo.
Mesa Verde National Park, Colo.
Independence, Kan.
Kiefer, Okla.
Bald Mountain, Wyo.
Cloud Peak, Wyo.
Sundance, Wyo.-S. D.

Under the most favorable conditions, the backslope of a cuesta may conform very closely to the dip of the capping layer of hard rock. The greater the contrast in resistance between the hard layer and the next overlying soft formation the more perfect will the stripping be and the more nearly will the gentle slope of the cuesta conform to the actual dip of the rock. When

that correspondence is perfect, it becomes possible, of course, to determine the dip by computing the topographic slope. The difficulty is to know, from the map, when the correspondence is most complete.

In this connection, a few general hints should prove helpful. Normal topographic slopes produced by erosion of homogeneous material are usually curves somewhat approaching sine curves in general shape. In other words, from the hill top the slope is usually gentle, then steepens on the hillside, and flattens toward the valley bottom. On the contrary, a dip slope is usually a straight inclined surface (Fig. 11). The longer and the more perfect this straight incline the more nearly, as a rule, will it approach to the actual dip of the beds.

The Mesa Verde (map of Mesa Verde National Park, Colo.), with its magnificent north-facing escarpment, and the long, straight, gently inclined profiles of its upland, sloping south or slightly east of south, probably illustrates, as well as any map made, dip slopes that are a close approximation to the true dip. The mesa in the southwest corner of sec. 10, T. 34 N., R. 16 W., and extending from there southeastward, affords a good specific example. This surface slopes somewhat east of south about 175 to 200 feet per mile, and this is probably rather close to the actual dip of the capping hard layer, though no detailed geological map is available by which the inference can be checked. Along the Government road between the Mummy Lake group and Spruce Tree House, Chapin Mesa slopes south or slightly southeast 725 feet in 4 miles, or at an average rate of about 180 feet per mile. Moccasin Mesa, farther east, in the first 2 miles south of the south line of sec. 36, T. 35 N., R. 15 W., slopes 400 feet, or 200 feet to the mile. In the next 2 miles it slopes 300 feet, or 150 feet to the mile. Such consistently regular slopes are probably controlled very closely by structure, and it is safe to infer that the average regional dip in the area is not far from 150 or 200 feet, that is, about 1½ or 2°.

There are, however, other factors to be taken into consideration in determining the reliability of a dip slope. If the soft bed over-

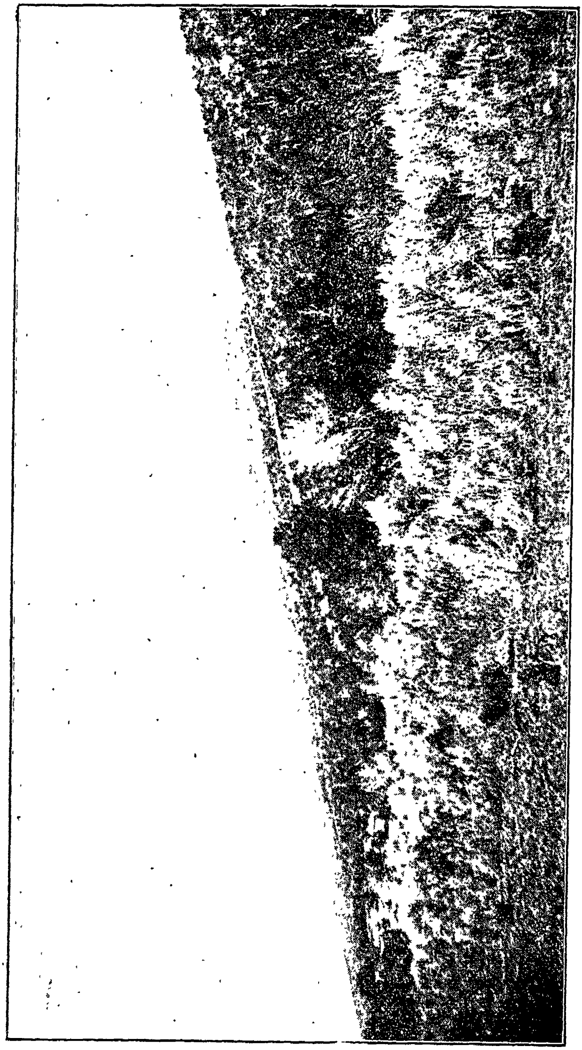


FIG. 11.—Dip slope on surface of Pennsylvanian limestone, Big Indian structure, San Juan County, Utah.

lying the cap rock is thin, and another escarpment occurs rather close, limiting the length of the dip slope, there may be a tendency for incomplete stripping of the surface of the hard layer on the lower portion of the slope, thus making the topographic incline less than the angle of dip of the beds, especially if the strike valley is not occupied by any considerable stream. This is likely to be the case on escarpments as close together as those in the W. ½ T. 31 S., R. 14 E., and the east edge of T. 31 S., R. 13 E., on the Independence (Kan.) quadrangle. In this instance the backslope is all but imperceptible, not exceeding 20 feet in 2 miles. The regional dip, however, is not much over 25 feet per mile, so that the backslope gives at least a fair idea of the very low dip prevailing.

Another condition encountered not infrequently is that of a large strike stream occupying the soft-rock belt and cutting down at a rate that increases the backslope, as, for instance, between Verdigris and Fall rivers (Independence sheet, Kan.). The escarpment is facing east over the Verdigris, but the west slope of the divide, toward Fall River, is as much as 160 feet in a fourth of a mile, which is far greater than the regional dip. Fall River has cut down so fast that it has not shifted west down the dip appreciably.

To sum up the situation, if escarpments are not too close together, so that the backslopes are incompletely stripped, if the backslope is not oversteepened by the cutting of a large river, and if the topographic profile is a fairly straight incline for any considerable distance, it may yield moderately dependable information regarding the amount of dip. In the cases cited in the following paragraphs, dip has first been determined as closely as possible from the topography and the results then checked from geologic maps or published descriptions. In general, results obtained thus are likely to give a figure somewhat less than the actual dip.

Kiefer. Okla.—On this map, the area where the backslope seems to be straightest and least interrupted is from the southeast corner of sec. 30, T. 17 N., R. 12 E., to the center of the west

line of sec. 26, T. 17 N., R. 11 E. In this distance the topography declines about 220 feet, or at a rate of 73 feet to the mile.

According to *United States Geological Survey Bulletin* 541, Plate III, the dip of the rocks in this distance is 250 feet, or an average of 83 feet per mile.

Apishapa, Colo.—Near the center of the east central rectangle, and just northeast of B. M. 5,117 is an asymmetrical hill with an escarpment facing southwest, the highest closed contour of which is 5,300 feet. The backslope of this hill, avoiding the valleys cut into it, is very nearly 200 feet in 2 miles. Determinations of dip made on the geological map at this point are 100 feet to the mile (Folio 186).

The backslope of Cordova Mesa (SW. rect.) on a line about N. 25° W. through the letter "s" of the word "Mesa" in a distance of 2 miles is about 100 feet, or 50 feet to the mile. The dip of the formations has been ascertained on the geologic map to be 50 feet to the mile.

Cloud Peak, Wyo.—At Ed Point (cent. rect.) the backslope, southwest from the highest contour, is about 800 feet in 2 miles, or about 400 feet per mile, which is slightly over 4°. The dip recorded on the geologic map (Folio 142) is 8°, seemingly a considerable discrepancy. Actual computation of the dip, however, from the geologic map, shows it to be not over 1,100 feet in 2 miles, or 550 feet per mile. The figure shown by the dip arrow must be local, and the 400 feet per mile determined on topography is a reasonably close approximation to the 550 feet determined by computation on the geological map.

Another such "flatiron" (NE. ¼ S. cent. rect.) points northeast, its apex marked by a closed 9,100-foot contour. Its backslope to the southwest is also 800 feet in 2 miles, or 400 feet to the mile. Its dip on the geological map is shown by symbol to be 7°, but determinations on the geological map do not average over 500 feet to the mile, for the 2 miles, the 7° again being somewhat local. The check is sufficiently close.

Bald Mountain, Wyo.—There is a pronounced escarpment on the south side of Shell Creek (SE. rect.) facing northeast, the

southwest slope of which is sufficiently regular to suggest structure. The slope is about 1,600 feet in 4 mile where most regular, or about 400 feet to the mile. The computed dip of the beds, from the geological map (Folio 141), is 1,700 feet in 4 miles, or only a little over 400 feet to the mile.

Sundance, Wyo.-S. D.—The divide on the east side of the word "Stockade" in the name Stockade Beaver Creek (SE. rect.) has a sufficiently straight profile to suggest dip slope. Its inclination in 2 miles, choosing that part with the most uniform slope, is 550 feet, or about 275 feet per mile, that is, about 3°. A dip arrow on the geological map (Folio 127) records 4°, whereas computation from the geologic map gives 350 feet in 1¾ miles, or 200 feet to the mile, which is slightly over 2°, as close a check as could be expected.

Naturally, in all the determinations made above, only such backslopes were used as suggest from the straightness of their profile that they are true dip slopes, conforming closely to structure. After favorable localities had been picked out, only such parts were used as did not seem to be unduly influenced by the proximity of valleys. In some cases both the upper and lower extremities of the slope may well be discarded, to avoid sudden changes, only the most regular portion being employed. It is freely admitted that the method has serious limitations, but under favorable conditions rather close estimates of dips between ½° and 10° may be made from topographic maps. With steeper dips, the estimates became less accurate for several reasons. Slopes probably correspond less closely with dips, contours are usually less accurately spaced on steep slopes, and distances are shorter and percentage errors, therefore, higher.

TOPOGRAPHIC EXPRESSION OF ANTICLINES

Maps

Cullman, Ala.
Fort Payne, Ala.-Ga.
Gadsden, Ala.
Scottsboro, Ala.
Stevenson, Ala.-Tenn.
Marysville Buttes and vicinity, Cal.
Axial, Colo.
Danforth Hills, Colo.
Monument Butte, Colo.
Paradox Valley, Colo.
Rangely, Colo.
Summitville, Colo.
Great Bend, Kan.
Russell, Kan.
Jonesville, Ky.-Va.-Tenn.
Davis, Md.-W. Va.
Piedmont, Md.-W. Va.
Wingate, N. M.
Bedford Pa.
Catawissa, Pa.
Confluence, Pa.
Donegal, Pa.
Johnstown, Pa.
Latrobe, Pa.
Lock Haven, Pa.
Meyersdale, Pa.
New Florence, Pa.
Pine Grove, Pa.
Somerset, Pa.
Williamsport, Pa.
Sturgis, S. D.
Chattanooga, Tenn.
Kingston, Tenn.
Pikeville, Tenn.
Pikeville special, Tenn.
Sewanee, Tenn.
Escalante, Utah.
Fish Lake, Utah.
Henry Mountains, Utah.
La Sal, Utah-Colo.
Manti, Utah.
Price River, Utah.
San Rafael, Utah.
Big Stone Gap, Va.
Wise, Va.
Elkins, W. Va.
Grass Creek Basin, Wyo.
Oregon Basin, Wyo.
Meeteetse, Wyo.

Since the beds in an anticline dip outward, escarpments, if they occur, should face inward toward the center of the uplift. Inward-facing escarpments (pp. 137–148) can be traced a considerable part, at least, of the distance around such domes as the Cincinnati arch, the Nashville dome, the Ozarks, and the Black Hills. Smaller dome-shaped uplifts completely encircled by inward-facing escarpments are also numerous, some nearly round, others slightly elongated.

Canaan Valley occupies the site of an elongated dome. On the Piedmont (Md.-W. Va.) sheet, it is mapped on a scale $\frac{1}{125,000}$, with a 100-foot contour interval. The Davis (Md.-W. Va.) sheet, a partial resurvey on the scale of $\frac{1}{62,500}$, with an

interval of 50 feet, shows the detail of the area much more completely. Canaan Mountain on the west and Cabin Mountain on the east constitute escarpments resulting from harder rock, underlain by a softer bed that has been etched out to form the lowland known as Canaan Valley. Backslopes are definite, but not sufficiently regular to permit measuring the angle of dip of the beds.

Below the bottom of Canaan Valley is doubtless another hard layer of rock which, as normal erosion progresses, will make its appearance as a central ridge, around which the lowland will circle in the form of a "race course". Such is essentially the situation on the Bedford (Pa.) quadrangle. Chestnut Ridge, in the central part of the map, is surrounded by a continuous lowland etched out on softer rock, though not occupied by any single stream. Overlooking this is an inward-facing escarpment, best shown east of the word "Quaker" of "Quaker Valley", with a very distinct southeast backslope, a feature also in evidence at Harmony Hill (E. cent. rect.). From the latter point the escarpment swings in a broad curve to Ryot (cent. rect.), where the backslope is less obvious, but is indicated by the large number of isolated knobs along its crest, back (west) of which is the hint of another lowland.

The escarpment results from a hard layer of rock, the encircling valley is etched out on softer beds, and Chestnut Ridge is another hard layer which had made its appearance centrally. If this second hard layer is, in turn, underlain by softer beds, it will, in the ordinary course of erosion, itself become breached, forming an inward-facing escarpment overlooking a central lowland etched out on the underlying soft beds.

A dome with an encircling escarpment, a "race course" lowland, a second or inner encircling escarpment, and a central lowland is shown on the Grass Creek Basin quadrangle of Wyoming. Beginning about an inch south of the east end of the fifty minute parallel is a south-facing escarpment which can be traced nearly straight west, to the southeast corner of the west central rectangle, from which point it swings strongly southeast, partly

enclosing a broad plain. The northward backslope is obvious, and the southwest backslope can be detected on the 6,230-foot knob just southwest of Wagonhound Spring (SW. rect.). In secs. 19, 20, and 21, T. 44 N., R. 98 W., the steep slope faces in the reverse direction, either as a result of overturned beds, or possibly of very steep dips (p. 152).

Within the main lowland is an oval group of hills occupying secs. 10, 11, 12, 13, 14, 15, and 24, T. 44 N., R. 98 W., and secs. 18 and 19, T. 44 N., R. 97 W. Within this range is a second and smaller inner lowland in secs. 13 and 14, T. 44 N., R. 98 W. The asymmetry of the hills in the NE. ¼ sec. 13, T. 44 N., R. 98 W. indicates northeast dips, but, as these hills are traced in either direction, the dips change, and with the changing dip the escarpment swings around to enclose the central lowland.

In this dome, then, we have two inward-facing escarpments, one encircling or "race course" lowland, and one inner lowland. Grass Creek Basin (N. cent. rect.) on the same map is a well-known Wyoming dome (Fig. 12).

A very striking dome with a well-developed central lowland and one inward-facing escarpment with distinct backslopes is Nippenose Valley, on the Williamsport and Lock Haven (Pa.) sheets. Mosquito Valley is a small dome along the same line of folding, on the Williamsport sheet.

Grassy Cove in the northwest part of the Kingston (Tenn.) sheet is a dome with a central lowland and an inward-facing escarpment, and is of especial interest, in that its drainage is subterranean. The lowland is actually a sink hole, though it is not shown (edition of 1891) with hachured contours.

Among well-known domes with encircling "rim rocks" or escarpments, enclosing lowlands, Grass Creek Basin (Grass Creek Basin quadrangle, Wyo.) has already been cited. Quite similar are Oregon Basin (Oregon Basin sheet, Wyo.) and little Buffalo Basin (Meeteetse quadrangle, Wyo.). Although structurally domes, these are locally known as basins, because of the lowland enclosed by the "rim rock". On the Meeteetse sheet, Spring Creek Basin, which suggests another dome, is really the end of a

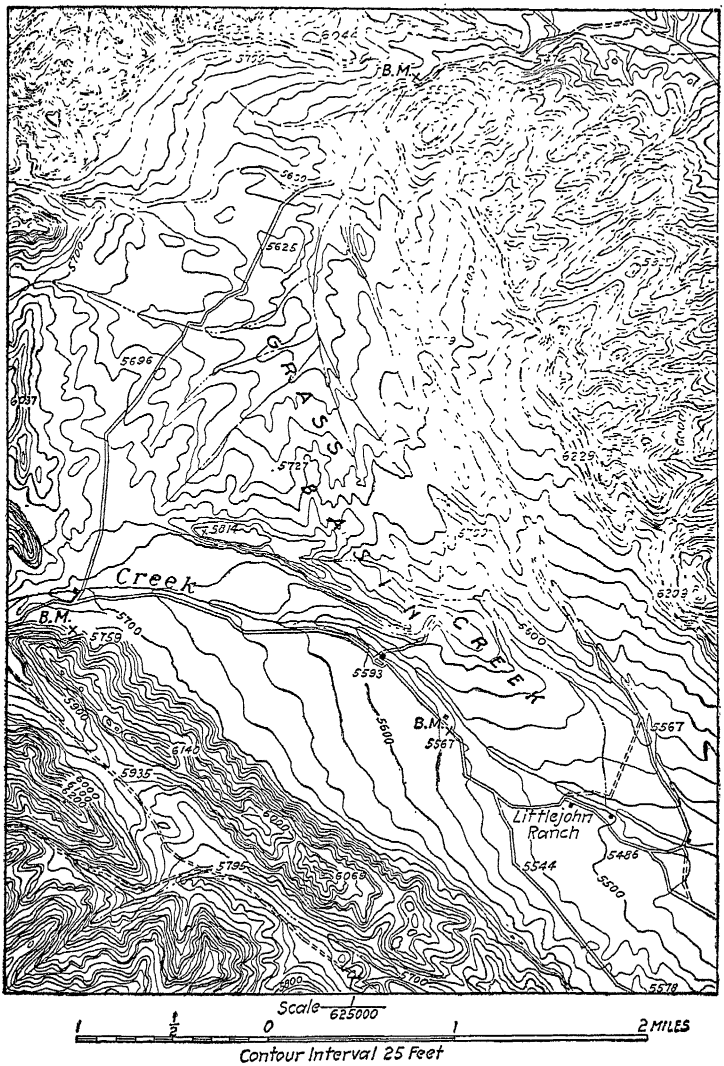


FIG. 12.—Dome with central basin and enclosing escarpment, Grass Creek Basin, Wyoming. (*U. S. Geol. Survey.*)

much longer anticline, according to the geological map. On the same sheet, Hole in the Ground (sec. 17, T. 48 N., R. 99 W.) suggests still another dome, though it does not seem to be so shown on available geological maps. The lowland at Renners Ranch (secs. 28 and 29, T. 47 N., R. 100 W.) corresponds to a mapped dome. The lowland in sec. 26, T. 47 N., R. 101 W. also resembles a portion of a dome, but does not correspond to the position of any fold shown on the geological map, which, however, is very generalized (*U. S. Geol. Survey Prof. Paper* 53, Pl. III) and inaccurate in detail.

A number of well-known domes also occur in Colorado. Raven Park, T. 2 N., Rs. 102 and 103 W., on the Rangely sheet has the usual enclosing "rim rock" and central basin. Another is Sinbad Valley, the Colorado portion of which is mapped on a scale of $1/125{,}000$, with a 100-foot interval (Paradox Valley sheet), the Utah portion (La Sal sheet, Utah-Colo.) on a scale of $1/250{,}000$, with a 250-foot interval. The enclosing rim and backslopes are evident on both maps.

A well-known anticline in Colorado, somewhat too long to be properly termed a dome, is Axial Basin. It is shown on the Danforth Hills sheet and in more detail on the Axial and Monument Butte quadrangles. The inward-facing escarpment is conspicuous, and the backslope a pronounced feature of the north limb. On the south limb it shows clearly only near the southeast end of the structure.

On the Summitville (Colo.) sheet, a small dome is shown in Tps. 32 and 33 N., R. 1 E. The east-facing escarpment with west backslope, almost a dip slope, shows clearly in sec. 5, T. 32 N., R. 1 E.; the northeast-facing escarpment in sec. 16, T. 32 N., R. 1 E.; and the northeast flank, on which dip cannot be made out, extends as a line of hogbacks from sec. 28, T. 33 N., R. 1 E., to sec. 7, T. 32 N., R. 2 E.

One of the most perfect examples of a dome with an inward-facing escarpment, probably, is Circle Cliffs (Escalante sheet, Utah), which is very inadequately mapped on a scale of $1/250{,}000$ with a 250-foot contour interval. There are two "rim rocks"

the smaller and inner (just east of the "l" of "Circle") being known as the "Little Rim", the larger and outer as the "Big Rim". The central highland is not conspicuous on the map. The entire area inside the "Big Rim" is known locally as Burr Flats, and there are very few practicable passes through the escarpment, the southeast curve of which is shown on the bordering Henry Mountains sheet.

Another very famous dome in Utah is the San Rafael Swell, shown chiefly on the San Rafael sheet, but extending onto the adjacent Price River and Fish Lake maps. There is a central highland, an encircling lowland, a very marked inward-facing escarpment, shown on either side of the words "San Rafael Swell", and to the north a second great plain known (Price River and Manti sheets) as Castle Valley, bordered on the north by Book Cliffs escarpment, the great loop of which is a response to the San Rafael uplift.

In New Mexico, the Zuni Mountains (Wingate sheet) constitute the central upland of a great dome, with inward-facing escarpments. One such escarpment (south of San Antonio Springs, E. cent. part of map) can be traced west parallel to the railroad, almost to Gallup, where it turns abruptly and continues southeast as a much steeper hogback to Inscription Rock on the south border of the sheet. Other parallel escarpments may be seen at numerous points, though the large interval and small scale of the map obscure much otherwise significant detail.

Domes resulting from laccolithic intrusion may, if the sedimentary beds show sufficient differences of resistance, result in inward-facing escarpments, as dissection proceeds. Mt. Ellen of the Henry Mountains group (San Rafael sheet, Utah) shows, on the east side, near the "s" of the word "Mountains", a number of small knobs with escarpments facing west and backslopes east, that surely result from tilted beds. A complete ring of such knobs surrounds Mt. Ellsworth (Henry Mountains sheet, Utah). With more detailed mapping, these would doubtless show as a striking escarpment. The dipping ash beds or lava flows of a considerably dissected volcanic cone may result

in entirely similar asymmetrical ridges, facing inward, as shown on the map of Marysville Buttes and vicinity (Cal.). Whereas the laccolithic uplift is a true dome, in the sense that the strata have actually been lifted, the dips in a volcanic cone may be largely initial, as a result of inclined deposition. The resulting topography, however, could probably not be distinguished, on a contour map, from that of a dome.

A conical hill in secs. 13, 14, 23, and 24, T. 6 N., R. 3 E., on the Sturgis (S. D.) sheet shows at several places on its periphery small hills that suggest fragments of an inward-facing rim, and point to outward dips. Its symmetry is sufficiently perfect to recall many of the volcanic cones described in a previous section (p. 61). The geologic map, however, shows it to be a dome on sedimentary rocks, probably above a laccolithic core.

A physiographic feature that has attracted considerable attention is the inward-facing escarpment about Cheyenne Bottoms (Great Bend and Russell sheets, Kan.). It has suggested to many persons a dome of the type described above. Field examination by the senior author, however, discovered no dips that should result in such structural control and no really satisfactory explanation of this peculiar physiographic feature seems to have been offered.

Among the more elongated anticlines, Sequatchie Valley is particularly famous. It is faced by two parallel escarpments with distinct backslopes. Its detail is best shown on the Pikeville special (Tenn.) sheet, but the great extent of the anticline may be more fully realized by a study of the Pikeville, Chattanooga, and Sewanee (Tenn.) sheets, across which the anticlinal lowland is occupied by Sequatchie River, and is known as Sequatchie Valley. It continues as Browns Valley across the Stevenson, Scottsboro, Gadsden, and Cullman (Ala.) sheets, and on the latter the inward-facing escarpments and backslopes are still distinctive features. Few anticlines are as regular as this, throughout such a great distance. Wills Valley, across the Stevenson, Fort Payne, and Gadsden (Ala.) sheets, is a parallel anticline of considerable regularity. The border between the folded

Appalachians and the Cumberland Plateau affords still other examples.

A very definite anticline is indicated by the topography on the Wise and Big Stone Gap (Va.) sheets, Stone and Powell Mountains facing each other over an inner lowland. Escarpment face and backslope are distinct. There is a fairly defined central elevation (Stocker Knob, S. cent. rect., Big Stone Gap sheet) within the lowland. Both Powell Mountain and Stone Mountain can be traced southwest onto the Jonesville (Ky.-Va.-Tenn.) sheet, where, because of steeper dips or poorer mapping, the escarpments and the backslopes lose their distinctive character, becoming so nearly equal on the map that the direction of dip is very imperfectly indicated.

Another good example, in which the contrast between escarpment and backslope is very pronounced, occurs on the Elkins (W. Va.) sheet, the lowland between Cheat Mountain and Rich Mountain being definitely anticlinal.

Sugar Valley (Williamsport and Lock Haven sheets, Pa.) is the central lowland on an anticline with good inward-facing escarpments and distinct backslopes. With further erosion any older hard bed would make a central highland.

The lowland between Ashland Mountain and Broad Mountain (Catawissa sheet, Pa.) is, obviously, anticlinal, the inward-facing escarpment and the backslope of Broad Mountain being unmistakable. The backslope of the Ashland Mountain limb is steep enough so that, considered by itself, its interpretation might be uncertain. Considered in conjunction with Broad Mountain, there should be no doubt of the anticlinal structure. On the adjacent sheet to the south (Pine Grove sheet, Pa.) the lowland splits, and another hard-rock ridge, on an older bed, occupies its center. This, in turn, splits into two ridges, Line and Mahantango, enclosing another inner lowland on a still older soft bed.

It sometimes happens that a hard-rock layer, overlain by softer material, may be etched into relief along the center of an anticline, with no higher beds sufficiently hard to produce

inward-facing escarpments. Such is the well-known Laurel Ridge anticline, which may be traced from the Johnstown (Pa.) quadrangle southwest across the New Florence, Somerset, Donegal, and Confluence sheets. A suggestion of inward-facing escarpment occurs on the Somerset sheet, along the east side of Laurel Hill Creek (SW. rect.) and along Loyalhanna Creek (NW. rect.). Wholly comparable is the Chestnut Ridge fold, across the New Florence, Latrobe, and Donegal (Pa.) sheets. At this stage in the dissection, the topography gives little evidence as to whether the ridge is anticlinal or synclinal.

Such a hard-rock ridge, marking the center of an anticline will ultimately, if underlain by softer beds, become breached, and a lowland be etched out on the soft beds, the two exposed edges of the breached hard layer becoming the two inward-facing escarpments. Negro Mountain anticline (Meyersdale sheet, Pa.) shows a ridge of this character in the initial stages of breaching. The headwaters of Isers Run (NW. cor. S. cent. rect.) are working along the axis of the fold, etching out a lowland with inward-facing escarpments and backslopes. The central lowlands is still farther advanced in its development in the extreme southwest corner of the map.

In areas where, because of steep dip, the ridges flanking a fold do not show sufficient asymmetry safely to indicate the direction of dip, the distinction between anticlines and synclines can sometimes be made, if the fold is pitching, by the character of the "elbow" where the two flanking ridges meet. Since this structure is intimately related to pitch, its discussion will be deferred to a later section dealing with that subject (pp. 175–180).

Attention should again be called to the fact that an anticline may be a mountain (Laurel Ridge, Johnstown sheet, Pa.), or that the mountain may become breached, with the beginning of a central lowland (Meyersdale sheet, Pa.). At a still later stage in the development, it may be a valley, with flanking ridges (Nippenose Valley, Williamsport sheet, Pa.). This appearance of central ridges and their breaching may be repeated as many times as hard beds underlain by softer rocks are cut through by

erosion. We may, therefore, find anticlinal mountains, anticlinal valleys, and all possible combinations of these with flanking ridges. It will be shown later (p. 175) that synclines may, likewise, be either valleys or ridges.

TOPOGRAPHIC EXPRESSION OF SYNCLINES

Maps

Fort Payne, Ala.-Ga.	Millersburg, Pa.
Gadsden, Ala.	Pottsville, Pa.
Stevenson, Ala.-Tenn.	Wind Gap, Pa.
Marsh Pass, Ariz.	Chattanooga, Tenn.
Paradox Valley, Colo.	Pikeville, Tenn.
Piedmont, Md.-W. Va.	Pikeville special, Tenn.
Plainfield, N. J.-N. Y.	East Tavaputs, Utah-Colo.
Somerville, N. J.	Price River, Utah.
Huntingdon, Pa.	San Rafael, Utah.

Davis, W. Va.-Md.

Since a syncline consists of a structural trough toward which the beds dip from at least two sides, synclinal escarpments, whenever they exist, should face away from each other, with their backslopes pointing toward the synclinal axis. The area between Backbone Mountain and Allegheny Front (Piedmont sheet, Md.-W. Va.) is a broad gentle trough, the escarpments of the two mountains facing outward, with the backslopes pointing toward each other. Within the south part of this broad syncline is the Canaan Valley anticline. On the Davis (W. Va.-Md.) sheet, the area between Canaan Valley and Allegheny Front is synclinal, being a detail of the larger syncline on the Piedmont sheet.

The area between the Paradox Valley anticline and the Gypsum Valley anticline (Paradox Valley sheet, Colo.) is typically synclinal, with its outward-facing escarpments and inward-facing backslopes, shown clearly on Davis Mesa and Anderson Mesa (W. cent. rect.). Davis Mesa, the southwest flank of the Paradox Valley anticline, facing inward with respect to the anticlinal lowland, is also the northeast flank of the syncline,

facing outward from the synclinal axis. Anderson Mesa, the northeast flank of Gypsum Valley anticline, facing inward over its lowland, is, likewise, the southwest flank of the syncline, facing outward from the structural trough. The plain between Orange Cliffs and San Rafael Swell (San Rafael sheet, Utah) is another broad gentle trough of larger proportions.

West Tavaputs Plateau (Price River sheet, Utah) and East Tavaputs Plateau (East Tavaputs sheet) constitute a synclinal warp about the south end of which the Book Cliffs escarpment makes a broad bend. In Beckwith Plateau, the escarpment faces nearly west and the backslope east, in compliance with east dip, whereas on Brown Cliffs the escarpment faces southeast, the backslope pointing to northwest dips. A very similar synclinal warp is shown in the trap ridges of First and Second Watchung Mountains (Somerville and Plainfield sheets, N. J.), which make a broad curve, so that the backslopes incline inward, nearly opposite to each other. Very similar is the syncline of Black Mesa (Marsh Pass sheet, Ariz.), on which the outward-facing escarpments, and inward-facing backslopes, in this case approximately dip slopes, are strikingly exhibited.

Walden Ridge, east of the Sequatchie anticline, is also a broad synclinal mountain, well shown on the Pikeville special, Pikeville, and Chattanooga (Tenn.) sheets, with notable outward-facing escarpments, and backslopes inclined inward. Entirely comparable are Sand or Raccoon Mountain on the Gadsden and Stevenson (Ala.) sheets, and Lookout Mountain on the Fort Payne (Ala.-Ga.) quadrangle.

On the Wind Gap (Pa.) sheet, Weir Mountain, with its north to northwest-facing escarpment and southerly backslope, is the north flank of a syncline, a south-facing escarpment of which can be seen at Rossland (cent. rect.). Outward-facing escarpments in the central and east central rectangles of the Pottsville (Pa.) sheet, with very distinct backslopes toward Landingville, indicate the east end of another syncline.

The Barrens (Huntingdon sheet, Pa.) represents a broad syncline of which Terrace Mountain is the northwest flank,

expressed in a remarkable escarpment facing northwest, in which the direction of dip is unmistakable. On Sideling Hill, the southeast flank, the indication of direction of dip is uncertain, the rocks being steep enough to result in a nearly symmetrical ridge. Broadtop Mountain is the reflection of the syncline on the next younger resistant stratum.

Thus synclines, like anticlines, may show more than one set of escarpments, the number depending on the number of hard layers, overlying softer beds, which can be etched into relief. Two pronounced escarpments occur on the synclinal warp of Watchung Mountains, on the Somerville and Plainfield sheets (N. J.).

Most of the synclines cited above are ridges, typical among which are Walden Ridge on the Pikeville special (Tenn.), Sand Mountain on the Gadsden (Ala.) sheet, and Lookout Mountain on the Fort Payne (Ala.-Ga.) quadrangle. Synclines may, however, be occupied by valleys or lowlands, as on the Millersburg (Pa.) sheet, the area between Mahantango Mountain and Berry Mountain being synclinal (state geological map of Pennsylvania).

RELATION OF PITCHING FOLDS TO TOPOGRAPHY

Maps

Rome, Ga.-Ala.	New Bloomfield, Pa.
Marsh Pass, Ariz.	Pine Grove, Pa.
Catawissa, Pa.	Pottsville, Pa.
Everett, Pa.	East Tavaputs, Utah-Colo.
Holidaysburg, Pa.	La Sal, Utah-Colo.
Huntingdon, Pa.	Price River, Utah.
Lykens, Pa.	Monterey, Va.-W. Va.
Millersburg, Pa.	Davis, W. Va.-Md.

Williamsport, W. Va.-Md.-Pa.

Hard-rock ridges are parallel in folds of no pitch, but meet at one end or the other of a pitching fold (Fig. 13), forming an *elbow*, or, in the case of several adjacent anticlines and synclines pitching in the same direction, a *zigzag* (p. 101 and Fig. 36). An elbow ridge results from the junction of Peters and Cove

Mountains on the New Bloomfield (Pa.) sheet, and a typical zigzag or double elbow is shown on the Hollidaysburg (Pa.)

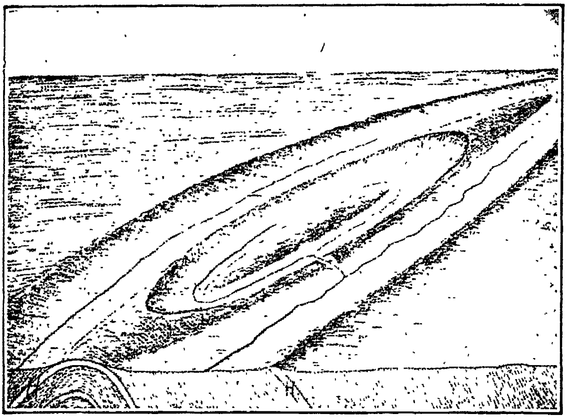


FIG. 13 *A*.—Diagram to illustrate the effects of erosion on a doubly plunging anticline made up of beds of unequal hardness. (*After Chamberlin and Salisbury.*)

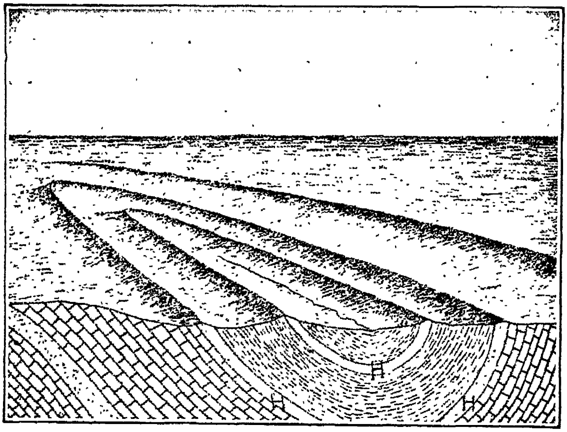


FIG. 13 *B*.—Effect of erosion on a plunging syncline made up of beds of unequal hardness. (*After Chamberlin and Salisbury.*)

quadrangle in the single long ridge mapped under the names of Dunning, Short, Loop, and Lock mountains.

In anticlines, the apex of the elbow points in the direction of pitch (Figs. 13 and 35), whereas in synclines it points opposite to the direction of pitch (Figs. 13 and 35). On the New Bloomfield (Pa.) sheet, therefore, since the fold represented by Peters and Cove mountains is synclinal (state geological map of Pennsylvania), it is pitching east opposite to the apex of the elbow. If a syncline and an anticline side by side both pitch in the same direction, the resulting elbows point in opposite ways (Hollidaysburg sheet, Pa.). It is, therefore, necessary to know the type of fold producing an elbow, before the direction of pitch can be read in the topography.

Of course, if the enclosing ridges show distinctive escarpments and backslopes, the problem is simple. On the Canaan Valley anticline (Davis sheet, W. Va.-Md.), the ridges come together in elbows at both ends, the one at the northeast end pointing northeast, the other southwest. This indicates that the northeast end of the fold is pitching northeast, the southwest end southwest. In other words, it is a doubly plunging or pitching anticline, or, better, an elongated dome.

The inward-facing escarpments and backslopes on Two Top and Cross mountains (NW. cor. Williamsport sheet, W. Va.-Md.-Pa.) show rather conclusively an anticlinal structure, and, since the apex of the elbow points south, the fold is pitching in that direction. The anticline between Ashland and Broad Mountains (Catawissa sheet, Pa.) is by the same evidence pitching slightly north of east, as is also Sugar Valley anticline on the Williamsport (Pa.) sheet.

The fold in the east central rectangle of the Pottsville (Pa.) sheet shows clearly by escarpment and backslope that it is synclinal. Since the elbow points east, the syncline is pitching west. The Black Mesa syncline (p. 174) on the Marsh Pass (Ariz.) sheet, by the same evidence, is pitching south, and the broad syncline indicated by the great curve in Book Cliffs (East Tavaputs and Price River sheets, Utah, p. 174) is pitching north.

On the Huntingdon (Pa.) sheet, Terrace Mountain and Sideling Hill, the two flanks of the broad syncline called the Barrens

(p. 174), do not actually meet within the area of the map, but it is obvious that, unless the pitch changes, they will meet in a short distance, so that the apex of the elbow points northeast, indicating southwest pitch. The area between Mahantango and Berry Mountains (Millersburg sheet, Pa., p. 175) is synclinal. Since these ridges are closer together to the southwest, the elbow will point in that direction, indicating pitch to the northeast.

Synclines and anticlines in parallel or nearly parallel position result in double elbows or zig-zags (pp. 101 and 175), an excellent example of which may be seen on the Rome (Ga.-Ala.) sheet. The asymmetry of Taylor Ridge in the northwest part of the map is strongly indicative of southeast dips. At High Point it makes a sharp elbow and extends nearly east to Crystal Springs. Although nothing can be inferred about dip from the shape of the east-west arm of this elbow, it is reasonable to assume that the area between the two branches is synclinal, in conformity with the dips indicated in Taylor Ridge. Since the elbow points southwest, the syncline pitches northeast.

Crystal Springs is at the apex of another elbow, the south arm of which is Simms Mountain. If the first fold is a syncline, that at Silver Hill and Cheney should be an anticline, pitching northeast in the direction of the elbow. The area between Simms Mountain and Lavander Mountain should, in turn, be another syncline, though some irregularity is evident at its west end, where the hook of Lavender Mountain breaks off so suddenly, as though by faulting. If it is a syncline, its elbow pointing southwest indicates northeast pitch.

Gaylor Ridge (W. cent. rect.) shows rather clear southeast dip. It makes an elbow near Holland, and turns south in a ridge that strongly suggests west dips, so that the area within the elbow is again synclinal, pitching southwest opposite to its apex. The Gaylor Ridge and Taylor Ridge synclines, pitching in opposite directions, suggest anticlinal cross-folding. All of these inferences can be verified in the Rome folio (No. 78).

The elbows of pitching synclines and anticlines differ from each other in certain significant respects that can best be appreciated

by reference to Fig. 13. In Fig. 13 *A*, the hard layer extends some distance beyond the junction of the two hard-rock ridges, as a point or spur to the elbow; whereas in Fig. 13 *B* the hard rock clearly ends at the junction of the ridges, so that there is nothing to form a spur, and the elbow of the syncline is blunt or rounded. Of course, if the pitch of the anticline is very steep, this hard-rock spur drops below erosion level in a very short distance, and may not be at all conspicuous. Furthermore, in special cases, the presence of excessive erosion, as of some large river adjacent to the end of the fold, may cut off such a spur, so that the presence of the spur indicates an anticline much more certainly than its absence does a syncline.

On the Monterey (Va.-W. Va.) sheet, Wilsons Run (E. cent. rect.) is entirely surrounded by a steep enclosing ridge, except for two water gaps and a wind gap. The inner and outer slopes of this ridge are so nearly equal that they give little or no indication of dip. Where the two lateral ridges meet on the northeast at Sounding Knob, they continue some distance as a single ridge or spur. At Duncan Knob on the southwest, they also form a distinct spur. The topographic indications are, therefore, that the fold is a doubly plunging anticline, the northeast end pitching northeast, the southwest end southwest. In the central part of the same map, Little Mountain and Monterey Mountain unite at Ladder House, and extend as a long spur, indicating an anticline pitching southwest.

Warrior Ridge (Everett quadrangle, Pa.) shows a very decided spur, and is known to be an anticline pitching south. The spur at the elbow in Dunning Mountain, on the west border of the map, also indicates an anticline pitching southwest. The curve in Sherman Valley (SE. rect., same map) lies between two successive elbows on the end of a syncline pitching northeast. Both the backslopes and the blunt ends of the elbows are indicative of the synclinal nature of the fold. A good syncline with outward-facing escarpments and inward backslopes occurs in the southwest rectangle of the same map. The north end pitches south and the south end north.

The elbow at the junction of Short Mountain and Loop Mountain (cent. rect., Hollidaysburg sheet, Pa.) is again a clear case of a north-pitching anticline with a short spur, and the elbow between Loop Mountain and Lock Mountain of a syncline pitching north with rounded loop. The synclinal nature is not to be seen in the slopes of the ridges, but is confirmed by the parallel synclinal elbow east of Robinson Run (SW. cor. NE. rect.) with its outward-facing escarpment and inward backslopes.

A situation like that at Sinbad Valley (La Sal sheet, Utah-Colo.) has sometimes proved confusing. The inward-facing escarpments and the backslopes are clearly enough developed, but there is no spur, in this case partly, at least, because the area outside the escarpment is not yet reduced enough by erosion to etch such a spur into relief.

The area between Berry Mountain and Peters Mountain (Lykens sheet, Pa.) has most of the topographic features of a syncline. Both mountains show steep outward-facing slopes, and gentle slopes inward, which would normally indicate synclinal structure, and consistent with this interpretation is the bluntly rounded elbow made by their junction. If, however, the next pair of mountains, Fourth or Stony on the south and Big Lick on the north, be traced east onto the Pine Grove (Pa.) sheet, the suggestion of anticline is quite as strong, the inward-facing escarpments and outward backslopes being fairly definite. An examination of the geological map of Pennsylvania shows that the structure is actually anticlinal. Although in many cases the structure may be indeterminate, this is one of the few known to the authors in which the topographic indications are so definitely misleading.

SYMMETRICAL AND ASYMMETRICAL FOLDS

Maps

Canyon de Chelly, Ariz.-N. M.
Marsh Pass, Ariz.
Apishapa, Colo.
Rome, Ga.-Ala.
Wingate, N. M.
Huntingdon, Pa.
Lykens, Pa.
Abajo, Utah-Colo.
Escalante, Utah.
Henry Mountains, Utah.
San Rafael, Utah.

Very commonly one flank of a fold is steeper than the other, and these conditions are often manifest in the topography, one hard-rock ridge indicating steeper dips than the other. The northwest escarpment of the San Rafael swell (San Rafael sheet, Utah), with its moderate backslope, indicates gentle dips, whereas the backslope of the southeast escarpment declines very suddenly, indicating much steeper dips. This is in striking contrast to the fold indicated by Line and Mahantango mountains, on the Lykens (Pa.) sheet, in which neither ridge indicates the direction or the amount of dip. The fold may or may not be asymmetrical, but the ridge slopes are so steep that all they suggest is high, though not necessarily equal, dips. Consequently, if both ridges of a fold are nearly symmetrical, as is so often the case with steep dips, it is not safe to assume that the fold is symmetrical. It may or may not be. If, however, one ridge by its symmetry suggests steep dips, and the other by its asymmetry points to dips of lower angle, the inevitable conclusion would be that the fold is asymmetrical.

On the Zuni uplift (Wingate sheet, N. M.), clearly marked escarpments north of Chaves (E. cent. part of map) may be traced west nearly to Gallup. Throughout that distance, the backslopes are such as to indicate moderate north to northeast dips. About 3 miles east and 3 miles north of Gallup, however, this escarpment swings sharply to the southeast, and entirely changes character, becoming a long, narrow string of steep hogbacks from which little hint may be obtained regarding the direction of dip. This string of hogbacks can be traced southeast to Navajo and Inscription Rock, and in the 20 miles from Mineral Springs to Nutria certainly indicates fairly steep dips. The anticline is asymmetrical, with gentle northeast and much steeper southwest dips. Of course, in an asymmetrical fold, the outcrop of a given bed is narrower on the steep than on the gentle flank, and, as a result of this condition, the crest or the central hard-rock ridge of an anticline (p. 165), if one exists, will be nearer the steeper limb. The crest of Zuni Mountains is closer to the southwest than to the northeast escarpment. In conformity

with this interpretation, the dips are toward the northeast on the northeast side of the main road between Agua Fria (SW. cor.) and Fort Wingate (cent. of map), the area of northeast dips being much wider than that of southwest dips.

The syncline west of Gallup (W. edge of map) is also asymmetrical. The ridge 3 miles south of Manuelito indicates very gentle dips to the northeast, as does also the one just south of Defiance. The other flank east of Gallup is much steeper.

The Circle Cliffs anticline (Escalante sheet, Utah) shows the same sort of contrast. Its northeast escarpment consists of steeply tilted ridges, whereas the opposite flank shows only a slight backslope. The northeast limb actually averages from 15 to 40° and the southwest from 2 to 4°.

The San Juan anticline is marked on the east by Comb Ridge (Abajo sheet, Utah-Colo.), a hogback indicating steep dips. It can be traced southwest onto the Canyon de Chelly (Ariz.-N. M.) sheet, where the southeast backslope becomes more gentle. Across the north part of the Marsh Pass (Ariz.) sheet, the escarpment swings from northeast-southwest around to southeast-northwest where, as on Skeleton Mesa and neighboring points, indication of dip is all but lost. At Clay Hill Divide (Henry Mountains sheet, Utah) there is only the faintest hint of backslope. The topographic features point to a structure with steep east and gentle west dips, and observations of 30 to 50° on the east flank, and 2 or 3° on the west, bear out the above inference.

The syncline of the Barrens on the southeast part of the Huntingdon (Pa.) quadrangle gives every indication on the map of being notably asymmetrical, the southeast dips in Terrace Mountain appearing to be gentle, whereas Sideling Hill, with its approximately equal slopes, gives a strong suggestion of steeper dips.

Taylor Ridge (N. cent. rect., Rome sheet, Ga.-Ala.) has a moderate southeast backslope, whereas the other limb of the pitching syncline, comprised in the ridge between High Point and Crystal Springs, with its nearly equal slopes, points to much steeper dips, and this interpretation is borne out by a study of

the geological map (Folio 78), which shows the southeast limb of the trough as much the steeper.

On the Apishapa (Colo.) sheet, an escarpment starting on the east side of Horse Pasture Canyon (N. W. rect.) can be traced southeast to the border of the map. It has a very definite dip slope to the northeast. A northwest-facing escarpment with much gentler backslope to the southeast occurs in the southeast part of the south central rectangle, and another in the southeast corner of the map. In the southwest rectangle, escarpments face north, on which the south backslopes are also very slight. This delimits the east portion of a dome or anticline, the northeast dips of which are distinctly steeper than those on the south side, and these deductions are again confirmed by the geological map (Folio 186).

Additional examples of topographic expression of folding

Bessemer special, Ala.
Birmingham, Ala.
Leeds, Ala.
Springville, Ala.
Vandiver, Ala.
Lower Matanuska Valley, Alaska.
Rampart, Alaska.
Echo Cliffs, Ariz.
Kaibab, Ariz.
Ray, Ariz.
Caddo Gap, Ark.
Hot Springs and vicinity, Ark.
Magazine Mountain, Ark.
Morrillton, Ark.
Cucamonga, Cal.
Piru, Cal.
Axial, Colo.
Daton Peak, Colo.
Durango, Colo.
Grand Hogback, Colo.
Higbee, Colo.
Ignacio, Colo.
La Plata, Colo.
Meeker, Colo.
Mesa Verde National Park, Colo.
Monument Butte, Colo.
Pueblo, Colo.
Red Mesa, Colo.
Timpas, Colo.
Waipio, Hawaii.
Galena, Ill.-Iowa.
Columbus, Kan.
Calhoun, Ky.
Morganfield, Ky.
Booneville, Miss.
Higdon, Mo.
Cut Bank, Mont.
Fort Custer, Mont.
St. Xavier, Mont.
Todd Lakes, Mont.
Long Valley, Nev.
Bernal, N. M.
Gallina, N. M.
Lamy, N. M.
Las Vegas, N. M.
Santa Clara, N. M.

Santa Fé, N. M.
Watrous, N. M.
Carthage, N. Y.
Watertown, N. Y.
Bainbridge, Ohio.
East Liberty, Ohio.
Atoka, Okla. (Ind. Terr.).
Sansbois, Okla.
Wewoka, Okla.
Winding Stair, Okla.
Bellefonte, Pa.
Bloomsburg, Pa.
Everett, Pa.
Harrisburg, Pa.
Mahanoy, Pa.
Millerstown, Pa.
Shamokin, Pa.
Wilkes-Barre, Pa.
Rapid, S. D.
Saint Onge, S. D.
Sturgis, S. D.
Cleveland, Tenn.
Murphy, Tenn.-N. C.
Ringgold, Tenn.-Ga.
Altuda, Tex.
Bone Spring, Tex.
Buck Hill, Tex.
Chispa, Tex.
Dove Mountain, Tex.
Hess Canyon, Tex.
Hood Springs, Tex.
Jordan Gap, Tex.
Marathon, Tex.
Monument Spring, Tex.
Nine Point Mesa, Tex.
San Carlos, Tex.
Tascotal Mesa, Tex.
Terlingua, Tex.
Ashley, Utah-Colo.
Bristol sheet, Va.-Tenn.
Natural Bridge special, Va.
Beverly, Wash.
Malaga, Wash.
Alderson, W. Va.
Clintonville, W. Va.
Dublin, W. Va.-Va.
Gerrardstown, W. Va
Onega, W. Va.
Parsons, W. Va.
Petersburg, W. Va.
Wardensville, W. Va.-Va.
Crandall, Wyo.
Gallatin, Wyo.
Ishawooa, Wyo.
Laramie, Wyo.
Newcastle, Wyo.-S. D.
Rock Springs, Wyo.
Sherman, Wyo.

TOPOGRAPHIC EXPRESSION OF FAULTS

Maps

Gadsden, Ala.
Vandiver, Ala.
Juneau special, Alaska.
Diamond Creek, Ariz.
Mt. Trumbull, Ariz.
Ballarat, Cal.-Nev.
Bishop, Cal.
Coalinga, Cal.
Elizabeth Lake, Cal.
Furnace Creek, Cal.-Nev.
Mt. Whitney, Cal.
Olancha, Cal.
Point Reyes, Cal.
Priest Valley, Cal.
Ramona, Cal.
San Mateo, Cal.
Searles Lake, Cal.
Loveland, Colo.
Guilford, Conn.
New Haven, Conn.
Honuapo, Hawaii.
Kalae, Hawaii.
Chester, Ill.-Mo.
De Soto, Mo.
Potosi, Mo.
Sullivan, Mo.
Weingarten, Mo.-Ill.
Poughkeepsie, N. Y.
Ramapo, N. Y.-N. J.
West Point, N. Y.
Oberlin, Ohio.
Kiefer, Okla.
Briceville, Tenn.
Burnet, Tex.
Abajo, Utah-Colo.
Castlegate, Utah.
Fish Lake, Utah.
Kanab, Utah.
La Sal, Utah-Colo.
Wellington, Utah.
Kilmarnock, Va.
Monterey, Va.-W. Va.

Faults may influence topography in a variety of ways. Recent faulting may produce true *fault scarps*, that is, cliffs or steep slopes. Such is the "earthquake fault" in Tps. 15 and 16 S., R. 36 E., on the west side of Owens Valley (Mt. Whitney sheet, Cal.). This scarp does not "catch" the necessary contours to be in evidence, and is, therefore, shown by hachures.

The Honuapo and Kalae (Hawaii) sheets, afford an excellent example of a recent fault scarp. The fact that the lava flows constitute a dip slope and that the scarp is parallel to the direction of dip, rather than at right angles, indicates that it is not a normal regional escarpment resulting from dipping beds. The almost undissected condition of the lava flows, as shown by the convention of saw-tooth pattern for rough lava surface, is evidence that the area has not been peneplaned. The extreme

straightness of the scarp indicates that it is too recent to have undergone much dissection.

It is rarely possible to tell, from the topographic map alone, how much a scarp has been modified by erosive processes. After such a cliff has been removed under the influence of erosion and re-excavated as a result of the juxtaposition of resistant and weak rocks, it becomes advisable, for the sake of precision, to employ another term, and call it a *fault-line scarp*.

Hurricane Ledge and Grand Wash Cliffs (Mt. Trumbull and Diamond Creek sheets, Ariz.) are definitely known from geological maps and reports to be related to great dislocations in the earth's crust, but it is quite probable that neither line of cliffs now occupies the actual site of the fault, though no positive evidence on the map can be noted. The great reentrant in the Grand Wash Cliffs, at Pollywog Spring (Diamond Creek sheet) seems to be the result of recession rather than the original shape of the escarpment, and implies considerable modification since the fault movement. If these scarps are actually along the sites of the dislocations, and have undergone but slight modification, they should be termed young fault scarps; if they are now some distance, by sapping and erosion, from the real trace of the fault plane, they may be spoken of as mature or old fault scarps; and if they have been completely removed and re-excavated, the term fault-line scarp is more appropriate.

Fault scarps, when newly made, are likely to be straight and regular, but as soon as they become modified somewhat, they can usually not be distinguished, on topographic maps, from simple regional escarpments. In fact, the Grand Wash Cliffs do not appear more straight and regular than the regional escarpment on the Kiefer (Okla.) sheet produced purely by erosion on very gently dipping layers of alternate hard and soft rock, an escarpment in no way related to faulting. Comb Ridge (Abajo sheet, Utah-Colo.) is also not related to faulting, yet is much more regular than the fault-line cliffs mentioned above. It is, there-

fore, obvious that on a topographic map fault scarps, fault-line scarps, and regional escarpments are often very difficult, if not impossible, to distinguish.

Since a normal regional escarpment implies harder layers capping softer beds, a very straight scarp in rocks that otherwise give evidence of massive character is, theoretically, indicative of a zone of displacement. Such is the east face of the Sierra Nevada Mountains, on the Olancha, Mt. Whitney, and Bishop (Cal.) sheets, a fault-line scarp of great magnitude. It is not sufficiently different, however, from the true regional escarpment on the Castlegate and Wellington (Utah) quadrangles to warrant any positive conclusion, from the topography alone, as to its origin or the nature of the rocks.

Scarps related to faulting are very numerous in the western states, those of the Colorado Plateau and Great Basin being well known. On the Fish Lake (Utah) sheet, the west face of Thousand Lake Mountain and the west face of Awapa Plateau, though more or less coincident with major dislocations, are probably fault-line scarps rather than fault scarps. From all that can be seen on the map, they might as well be simple regional escarpments, purely erosional on alternating hard and soft beds, as are Vermilion and White Cliffs (Kanab sheet, Utah). The scarp on the east side of Parowan Valley (Kanab sheet), which rather closely coincides with a fault, is no more easily distinguished from a true regional escarpment.

It not uncommonly happens that faults are completely truncated by erosion, so that their trace outcrops across a nearly perfect plain. For example, on the Sullivan (Mo.) quadrangle a fault with a throw of about 100 feet crosses the plain along the railroad about halfway between Fanning and Cuba, and another just east of Leasburg has about the same displacement. On the De Soto (Mo.) sheet, a fault with over 500 feet of throw crosses the S. ½ T. 39 N., R. 4 E., and produces not the slightest topographic effect, through most of the distance. A fault zone with an aggregate throw of 1,000 feet or more passes near Lithium (Chester sheet, Ill.-Mo.) and has been traced northwestward

between Minnith and River Aux Vase (Weingarten sheet, Mo.-Ill.). Along this zone there is no true scarp, either fault or fault-line, though locally minor details of the topography too small to show on the available maps correspond to certain faults, no one of which, however, would even be suspected from a study of the topographic map alone.

After a fault in which movement has completely ceased has reached this stage of effacement, it will never again, with any amount whatever of further erosion, produce another scarp, except through the juxtaposition of beds of unequal resistance. Depending upon the position of these beds, the fault scarp may face in the same direction as before (*resequent* fault-line scarp) or in the opposite direction (*obsequent* fault-line scarp).

It may, from the nature of the case, be very difficult to prove that a fault-line scarp is resequent, since it faces in the same direction as the original scarp. If, however, the dropped side is topographically the higher and overlooks a lowland carved on the raised block, the scarp is not original, but faces in the opposite direction and is clearly obsequent.

It is highly probable that many of the fault-line scarps of the Colorado Plateau and Great Basin are actually resequent, though the evidence is often inconclusive. Since, however, some of them are obsequent, it is to be expected that closely associated scarps may be resequent.

An especially notable example of an obsequent fault-line scarp is the east face of Walden Ridge on the Briceville (Tenn.) sheet. Although the southeast side has been raised, it is now topographically much lower than Walden Ridge, on the down-thrown side. From the topography alone, this scarp is not distinguishable from the escarpment of Cumberland Mountain (same map), which results from simple dip without faulting.

Another case of reversal occurs on the Burnet (Tex.) quadrangle. Backbone Ridge (SW. rect.) is a dropped block, and its original scarps must have faced inward over a lowland. Now, however, it is an upland; the scarps have been reversed, and are properly termed obsequent fault-line scarps. Of

especial interest is the fact that the lowland (Folio 183) is carved on granite, the upland on limestone. Although under certain climatic conditions a limestone might be more resistant than a granite, it is far more probable that the lowland was carved largely on other and softer beds, the stripping away of which has uncovered an old surface of granite. Again, these scarps are not essentially different from ridges produced by pitching folds, and the topography alone gives no certain indication of faulting.

A somewhat obscure obsequent fault-line scarp facing south over the raised but more deeply eroded block is shown on the Potosi (Mo.) quadrangle, trending nearly east and west, just south of Hunters Mill (SE. rect.). The map gives no evidence that it is of fault origin.

Graben and *rift valley* are terms commonly employed to designate lowlands produced by faulting. Though often used interchangeably, the terms are not strictly synonomous. The term "graben" seem to have been first used to indicate a topographic lowland on a block dropped between two faults. Of course, such a lowland may be original, or there may have been perfect peneplanation, and the arrangement of hard and soft beds have been such that a lowland was reexcavated on the same site, that is, the graben may be resequent.

The inward-facing escarpments with definite backslopes in the northwest quarter of the La Sal (Utah-Colo.) sheet mark the site of an anticline, the central portion of which is dropped between two faults, forming a lowland. If this lowland has existed as such since the faulting, it is properly spoken of as a graben. If it has been peneplaned and reexcavated in response to the arrangement of hard and soft rocks, it might be called a resequent graben. There is little or nothing in the topography to indicate that the anticline is complicated by faulting.

It would hardly be proper to speak of an obsequent graben, since the original lowland, were the scarps obsequent, would become a highland, as in Backbone Ridge on the Burnet sheet, described on page 188, and the term "graben" would, therefore, no longer be applicable.

In the Far West, particularly in California, Nevada, and Utah, are many great intermontane basins without outlet to the sea. Of course, it is possible that a basin with outlet might, by decrease in rainfall, have that outlet so choked by talus as to transform it into an enclosed area. Nevertheless, many of the deeper of these great depressions are probably structural. Stream erosion could not have carved these so deeply below their outlets, and it is unlikely that wind could have scoured at least the major ones. They are, therefore, probably the original result of the deformation, and not resequent. Among these, then, we may look for typical grabens.

Saline Valley (Ballarat sheet, Cal.-Nev.), the bottom of which is about 2,500 feet lower than the lowest notch in its rim, would certainly, even from the topographic map alone, be considered a structural depression. Comparison with the fault map of California[1] shows that it lies between two faults. Panamint Valley and Death Valley (Ballarat, Searles Lake, and Furnace Creek sheets, Cal.-Nev.) are also dropped blocks, to which the name "graben" properly applies.

Tomales Bay (Point Reyes quadrangle, Cal.) lies between two bounding faults,[1] and is probably a true graben. Although glaciation can do much to straighten a valley, the remarkably parallel sides of Gastineau Channel (Juneau special map, Alaska) are strongly suggestive of structural control, probably faulting, though the available map (*U. S. Geol. Survey Bull.* 502) gives no clue to the structure.

The term "rift valley", though it includes true grabens, or strictly tectonic lowlands, seems also to include valleys along a single fault. These may result from simple tilting of the fault block, or from the inferior resistance of the brecciated zone, or because of the juxtaposition of narrow belts of harder and softer beds on tilted blocks.

Rift valleys that are presumably not true grabens but more probably etched along brecciated zones of inferior hardness, are well shown on the San Mateo (Cal.) sheet, the San Andreas Rift, occupied by Crystal Springs Lake and San Andreas Lake,

[1] Seismological Society of America.

being especially conspicuous. Of similar character is probably the lowland along Anaverde, Leonis, and Pine Canyon valleys (SW. part of Elizabeth Lake sheet, Cal.); the lowland along Temecula Creek and Canada Aguanga (NW. part Ramona quadrangle, Cal.); and the one along Ragged Valley (T. 18 S., Rs. 14 and 15 E., Coalinga sheet, Cal.).

A topographic highland on a block raised between two faults is known as a *horst*. The Panamint Range between Death Valley and Panamint Valley (Ballarat, Searles Lake, and Furnace Creek sheets, Cal.-Nev.) probably fulfils the essentials of horst structure. As with a graben, a horst may be completely planed away by erosion, and be etched into relief again without further faulting, if the relation of hard and soft beds is favorable. In such a case it is resequent. The Panamint Range, however, could hardly be a resequent example, since these valleys could not be cut by erosion so far below their outlet notches. The notable scarp on the northwest flank of the Highlands, from Matteawan northeast (West Point and Poughkeepsie sheets, N. Y.), follows a zone of faulting, as does also the one on the south flank, from Peekskill southwest across the Rampo (N.Y.-N.J.) sheet. It is altogether likely that this region was completely peneplaned after the faulting took place, and that with general reelevation and consequent rejuvenation, the raised block between these zones was again etched into relief because of its superior resistance. It may therefore properly be termed a resequent horst, and the scarps resequent fault-line scarps. If the scarps of an original horst became obsequent, the horst would, of course, lose its essential upland character.

Alternating grabens and horsts, or a succession of parallel rifts, may produce a type of drainage known as a fault trellis. This type of trellised drainage is well shown on the San Mateo and Priest Valley (Cal.) sheets. In the classical California area, such a fault trellis is usually less closely spaced than that developed on alternate hard and soft tilted strata, and the blocks between the faults usually show a tendency toward dendritic dissection. The fault trellis also commonly shows fewer of the

right-angled turns in stream courses so common on the trellised pattern on simply folded beds (pp. 103 and 129). To make this contrast clearer, compare with the above maps the Monterey (Va.-W. Va.) and Vandiver (Ala.) sheets.

Although the facts cited above regarding the influence of faulting on topography are of great significance in any structural study, it must be emphatically repeated that most of the fault features described in the foregoing pages cannot be recognized from the topographic sheets alone. There are, however, certain examples of faults, the existence of which can be inferred with some certainty, merely from the topography. For instance, Murfree Valley (Gadsden sheet, Ala.) shows the inward-facing escarpments and backslopes of a typical anticline. The fold strikes about N. 50° E. and pitches northeast. Within the main escarpment is a second one called Red Mountain. This mountain is wholly distinct along the northwest flank of the fold, but is missing on the southeast flank. It is quite inconceivable that an unconformity or lensing of a bed should be sufficiently regular to produce this effect in a straight line, and still more so that that line should happen to coincide with the axis of an anticline. Furthermore, if such were the case, Red Mountain should not turn at the northeast end of the fold, and butt against the outer escarpment. The plausible explanation is that the outcrop of the formation producing Red Mountain is cut out of the southeast flank of the fold by a strike fault (Folio 35).

Another example of the rather obvious interpretation of faulting from the topography occurs on the Loveland (Colo.) quadrangle. Here the front ranges consist of hogbacks on tilted hard and soft beds, with subsequent strike valleys and numerous wind and water gaps. West of these hogbacks is an area of more nearly dendritic drainage, carved on rocks obviously more massive, presumably the crystalline core of the range. Now, in secs. 12 and 13, T. 6 N., R. 70 W., and secs. 18, 19, and 30, T. 6N., R. 69 W., is an isolated area of rock which appears, from its topography, to be identical with that forming the core of the main range. The logical interpretation would be that it is

elevated to its present position either by an anticline, or by a fault.

The two hogbacks on the east of this isolated mass appear to result from *two* hard layers or ridge makers. These may be traced south to a distinct elbow of a south-pitching anticline, but just around the curve of the elbow they end abruptly, as though cut off by a fault. This inference of faulting is greatly strengthened by the fact that between this isolated area of massive rocks and the main core of the range are only two hogback ridges, whereas, within the intervening syncline, were there no fault, there should be four—two hard layers dipping one way on one side of the trough, and the same two repeated, on the opposite side. The evidence is, therefore, strongly in favor of the interpretation of a fault striking northwest, an interpretation borne out by a study of the state geological map of Colorado.

The New Haven and Guilford (Conn.) sheets illustrate a principle sometimes valuable in the interpretation of faults. Pond Rock (SE. part New Haven sheet) and its companion, Totoket Mountain (E. cent. rect. New Haven sheet and W. cent. rect. Guilford sheet), are curved parts of a trap sheet interbedded in the Triassic sandstone of the Connecticut Valley lowland. Each curve represents a part of an irregular syncline and the area between them at Linsley Pond is the nose of an anticline, all pitching east. The anticlinal nose and both synclines have been truncated by a fault that runs roughly along a line from Beacon Hill (S. cent. rect. New Haven sheet) northeast through Linsley Pond and Lake Quonnipaug, past Bluff Head. Minor valleys in the brecciated zone, such as those from Linsley Pond southwest to the second "r" in "Hartford" ("New York, New Haven and Hartford R.R.") mark the detailed trace of the fault. The significant feature is the abrupt manner in which tilted ridges of hard rock in a bedded series abut against an area of rocks showing little or no evidence of similar structure, and along a line straight enough to suggest a zone of displacement.

Wave-cut terraces show escarpments that might easily, under certain conditions, be mistaken for fault scarps. Such

features are shown on the Kilmarnock (Va.) and Oberlin (Ohio) sheets. It has already been pointed out (p. 147) that such escarpments may be confused with regional escarpments resulting from gently dipping beds, and hints suggested for their discrimination. Much the same criteria apply in the case in hand. Wave-cut cliffs either face an existing body of water, or at least usually overlook a plain obviously a lake basin or coast-tal plain, because in general, sufficient dissection to destroy wholly the evidence of lake or marine plain would also obliterate the cliff. The entire absence of other evidences of the existence of a water body of sufficient size to cut such cliffs is presumptive evidence that the cliffs in question are not wave-made. Of course, along the shores of old lakes, both wave-cut cliffs and fault scarps may occur in close proximity, especially in areas like the Great Basin, where recent faulting and extensive abandoned shore lines are both abundantly developed. In such areas discrimination from a topographic map might be wholly impossible.

River terraces (alluvial) might also be confused with faults, in rarer instances. As a rule, however, the terrace, if traced far enough, will show fragments on both sides of the river, thus giving the clue as to its origin.

Additional maps showing the influence of faulting on topography

Anaheim, Cal.
Bryson, Cal.
Caliente, Cal.
Cholame, Cal.
Cucamonga, Cal.
Downey, Cal.
Elsinore, Cal.
Haywards, Cal.
Holtville, Cal.
Karquines, Cal.
McKittrick, Cal.
Morgan Hill, Cal.
New Almaden, Cal.
Palo Alto, Cal.
Pomona, Cal.
San Benito, Cal.
San José, Cal.
San Miguel, Cal.
Santa Rosa, Cal.
White Mountain, Cal.-Nev.
Farmington, Conn.
Holyoke, Conn.-Mass.
Meriden, Conn.
Dongola, Ill.
Equality, Ill.
Golconda, Ill.-Ky.
Passaic, N. J.-N. Y.
Raritan, N. J.
Trenton, N. J.-Pa.
Elizabethtown, N. Y.

Lake Pleasant, N. Y.
Mt. Marcy, N. Y.
North Creek, N. Y.
Schroon Lake, N. Y.
Carson Sink, Nev.
Tonopah, Nev.
San Marcos, Tex.
Van Horn, Tex.
Beaver, Utah.
Manti, Utah.
Salt Lake, Utah.
St. George, Utah.
Wellington, Utah.

TOPOGRAPHIC EXPRESSION OF UNCONFORMITY

Maps

Nome, Alaska.
Diamond Creek, Ariz.
Flagstaff, Ariz.
Ballarat, Cal.-Nev.
Charleston School, Cal.
Cholame, Cal.
Cucamonga, Cal.
Haywards, Cal.
Indio special, Cal.
Mare Island, Cal.
Mt. Whitney, Cal.
Paulsell, Cal.
Rock Creek, Cal.
San Antonio, Cal.
Santa Anna, Cal.
Fort Collins, Colo.
Cambon, Fla.
Macclenny, Fla.-Ga.
Oahu, Hawaii.
Mountain Home, Idaho.
Chester, Ill.-Mo.
Holyoke, Mass.
Hamilton, Mont.-Idaho.
Lexington, Neb.
Staten Island, N. J.-N. Y.
Playas, N. M.
Cohoes, N. Y.
Elmira, N. Y.
Kaaterskill, N. Y.
Hickory, N. C.
Morgantown, N. C.
Perry, Ohio.
Atoka, Okla.
Beaver, Pa.
Elk Point, S. D.-Neb.-Iowa.
Briceville, Tenn.
Greenville, Tenn.-N. C.
Roan Mountain, Tenn.-N. C.
Courtney, Tex.
El Paso, Tex.
Kendall, Wis.
Mauston, Wis.

Unconformities, particularly certain types which involve a great difference in age, structure, or hardness of the rocks, are very often apparent on a topographic map. A simple illustration is the mountain apron. Perhaps no map illustrates this type better than the Cucamonga (Cal.) sheet. The great mountain range is, evidently, an area of massive, hard rocks, long exposed to erosion; the plain at its base is newly built from the waste of the mountain range. The base of the mountain, or border of the plain, marks the approximate trace of the unconformity, which undoubtedly extends southward beneath the plain, at an unknown depth. Unconformities of this type are illustrated on numberless sheets in the Rocky Mountain and Pacific Coast states. In some cases they represent a break between the filling of intermontane basins and their bordering ranges (Ballarat, Cal.-Nev.), in other cases between the alluvium of wide valleys and the adjacent mountains (Mt. Whitney,

Cal. or Hamilton, Mont.-Idaho). Scarcely different from these are the well-known bolson plains of the Southwest, in which a broad filling of alluvium has all but buried the remnants of once prominent mountain ranges (Playas, N. M., or El Paso, Tex.). Probably of similar origin are the areas of hill and lowland in the Paulsell (Cal.) sheet. As a general rule, the width of the unbroken valley fill is roughly proportional to its thickness and indicates something of the amount of sediment to be expected. Thus, the Cucamonga and El Paso sheets undoubtedly indicate fillings several hundred, or possibly even a thousand, feet in depth. The filling of a large basin such as Saline Valley (Ballarat, Cal.-Nev.) is commonly deeper than that of a relatively small basin like the nearby "Race track". In areas where isolated bedrock exposures are numerous (N. E. part El Paso sheet), the filling doubtless is much thinner than in the unbroken central plain of the same bolson.

Such unconformities do not differ materially from those between the alluvium of any aggraded valley and the older rocks of the region it transverses. A good example is the Chester (Ill.-Mo.) sheet, on which the flood-plain lowand is evidently underlain by recent alluvium. This is much younger than the rocks of the adjacent highlands and undoubtedly rests upon them unconformably in a channel carved by the river. The trace of the unconformity is, of course, the boundary between flood plain and highland. Other examples are the Courtney (Tex.), Lexington (Neb.), and Elmira (N. Y.) sheets.

Still another simple type of unconformity is that in which deposits of a coastal plain, either marine or terrestrial, overlap onto an oldland of different character and history. The Haywards, Mare Island, and Santa Anna (Cal.) sheets afford good illustrations. The filling of recently deposited and undissected sediment abuts against an oldland long ago uplifted and much eroded. The island of Oahu (Hawaii) with its fringing deltas, especially near Honolulu, is typical. So also is Nome, Alaska (*U. S. Geol. Survey, Bull.* 533). Our Atlantic coast offers fewer obvious illustrations, mainly because the later deposits overlap

an oldland that was extensively peneplaned along a surface corresponding closely to the slope of the present sediments. A suggestion of the relations can be seen on the Staten Island (N. J.-N. Y.) sheet, where the main ridge constitutes an oldland partially surrounded by later outwash plains. The same principles of interpretation apply to these as to the interior deposits.

In all such cases older and often more or less disturbed sediments, which may not be actually exposed, may occur between the superficial alluvium and the bedrock represented by the adjacent highlands, but their presence may not be indicated by any evidence in the topography.

Terracing, either by streams or by wave work, implies unconformity between the deposits of the terrace level and those of the adjacent higher lands. Therefore, the recognition of a terrace also generally implies the recognition of an unconformity. Thus, on the Beaver (Pa.) sheet the distinct alluvial terraces at Shippingport and at Bellowsville undoubtedly represent valley filling of unconsolidated material much younger than and resting unconformably against the rocks of the upland which encloses the Ohio River Valley. The same is true of the wide terrace in the northwestern part of the Elk Point (S. D.-Neb.-Iowa) sheet. Here the present flood plain of the river constitutes clearly a second and still younger deposit, unconformable against the material of the terrace, and this, in turn, against the rocks of the upland. In general, the deposits of younger terraces lie lower in actual elevation than the exposed parts of older deposits that frequently constitute adjacent higher terraces. Thus, on the Cohoes (N. Y.) sheet west of Schaghticoke, levels can be distinguished at about 100 (present flood plain of Hoosic River), 200, 300, and 400 feet, each presumably floored with deposits younger than and unconformable against those of the next higher level.

Rock terraces, such as those of the Diamond Creek (Ariz.) sheet, of course, do not imply unconformity, and the same cautions given on pages 100 and 118 should, accordingly, be exercised in their interpretation.

Wave-made terraces mean unconformity if they are actually covered by a deposit of later material. They may be simple rock-cut benches, and then merely indicate planation of the adjacent rocks, and so have no significance with respect to unconformities. Very often planation near the inner edge of the terrace is combined with deposition on its outer margin, the terrace being partly "wave-cut" and partly "wave-built". With terraces that show clear evidence of deposition in the form of beach ridges (p. 54) or otherwise, the deposit is presumably unconformable against the adjacent higher land, or higher terrace, although it may be impossible to locate the exact limits of the deposit. Thus, on the Perry (Ohio) sheet it is safe to assume that the deposits of North Ridge are younger than and unconformable with respect to those of South Ridge, which, in turn, are unconformable upon still older rocks farther south. Again, the deposits of the irregular ridge in the eastern part of the Cambon (Fla.) sheet are younger than and unconformable with respect to those of Trail Ridge (Macclenny sheet, Fla.-Ga.). Practically, although a considerable part of the wave-made terrace may have been formed by cutting rather than by filling, it is seldom that the cut portion does not contain at least a thin veneer of sediment, and in mapping such terrace deposits the boundaries generally coincide with the area of the terrace. There are cases, however, where the cover either was absent or has since been stripped away, and the terrace, therefore, does not signify an unconformity.

A notable difference in structure of the underlying and overlying rocks often characterizes an unconformity and may serve to indicate its existence and location on a topographic map. On the Charleston School (Cal.) sheet the distinct tendency toward trellised drainage in the hills of the southwest corner suggests a folded or faulted region, whereas the alluvial deposits to the northeast doubtless are undisturbed. Unconformity might, therefore, be suspected and can be verified on the geological map of California. Similar conditions are suggested on the Cholame (Cal.) sheet, where folded ridges are evident in the

northeast part of the map, and a prominent rift valley extending from the northwest to the southeast corner also affects the older dissected beds but not the younger alluvial deposits of the basins.

The overlying undisturbed beds are by no means always or necessarily young and unconsolidated, although good maps showing discordance between rocks of the older sedimentary periods seem to be surprisingly few. The Atoka (Okla.) sheet is a fair illustration. Numerous curved and asymmetrical ridges in the north third of the map show that the rocks there are more or less folded, whereas the dendritic drainage and lack of such ridges on the southern two-thirds indicates flat-lying beds. The northern area is one of folded and faulted Paleozoic rocks, the southern is underlain by undisturbed Cretaceous beds (Folio 79). The line of contact is irregular and can only be located approximately from the topography.

The presence of folded beside unfolded rocks may merely indicate the dying out of the forces that produced the folds and is by no means a proof of unconformity. Thus, on the Kaaterskill (N. Y.) sheet we have in the southeast part of the map a lowland with conspicuously trellised drainage indicating sharp folding. West of it is a highland, the eastern escarpment of which points to west dips, but with a typical dendritic drainage farther west indicating comparatively flat-lying rocks. The difference in structure, which can be verified in the field or on a geological map, results mainly from a dying out of the folding in a series of beds characterized by no marked angular discordance. Many similar instances could be cited from along the border of the folded Appalachians and the Cumberland-Alleghany Plateau, as well as elsewhere. Very often they are complicated by faults along the contact (Briceville sheet, Tenn., and Folio 33).

The discordance in structure between a series of folded beds of varying hardness and the igneous or metamorphic bedrock (oldland) on which they were deposited is frequently expressed plainly in the topography. The Fort Collins (Colo.) sheet is a

good illustration. The mountains at the west side of the map belong to a crystalline complex on which the drainage is essentially dendritic. They are flanked by a narrow belt of sharply folded rocks, presumably sedimentary and generally seeming to dip outward as if they represented the flanking sediments about an uplifted mountain range. There are two principal hogbacks of hard rock on the map. The unconformity lies in a subsequent valley just west of the western ridge. On this sheet one might readily assume that the rocks of the eastern half of the map, showing little or no evidence of folding, were unconformable also with respect to the folded ridges. Such seems not to be the case, however, the contrast resulting merely from the rapid dying out of folding in a series of nearly parallel sedimentary beds (geological map of Colorado). Though several breaks are known within the sedimentary series, they are not revealed in the topography.

Comparatively regular contacts between crystalline rocks and unmetamorphosed folded beds may also result from faulting, as is very often the case at the eastern border of the Great Valley in the Appalachians. A small area in the southeast corner of the Greenville (Tenn.-N. C.) sheet, with high relief and dendritic drainage, contrasts strongly with the neighboring area of trellised drainage on softer folded but unmetamorphosed beds. The contact is approximately along a fault line (Folio 118). The Roan Mountain (Tenn.-N. C.) sheet affords another rather complex illustration (Folio 151). Such contacts cannot usually be distinguished from unconformity by topography alone.

A mere difference in the *character* of topography and amount of relief may serve to distinguish an unconformable series. In the southeast corner of the Indio special (Cal.) sheet three areas can be distinguished. The Santa Rosa Mountains exhibit high relief, dendritic drainage, and a fine-textured topography, all of which in this area might be assumed correctly to indicate crystalline rocks. At the southern tip of these mountains, extending up approximately to the 1,000-foot contour, is an area of much less relief, but apparently of infinitely more intricate

dissection, although the scale and the interval are poorly adapted to show it. This is known to be typical "badlands" topography, developed here on soft tilted beds probably of Pliocene age. Lastly, there is flat, undissected valley fill. The Pliocene beds are unconformable above the crystallines and beneath the alluvium. Similar marginal areas of tilted Tertiary strata are common about many western mountain ranges, although poorly shown on the prevailing small-scale and large-interval maps. The fringe of foothills bordering Mohave Desert (Rock Creek and San Antonio sheets, Cal.) suggests a similar situation, apparently verified on the much generalized state map. The same belt continues onto the Hesperia sheet and might be expected to include at least a considerable part of the detached hills north of Horsethief Canyon and Mojave River, which, however, are mapped as "plutonics".

Igneous features sometimes constitute recognizable unconformities. The flat upland in the southwest half of the Mountain Home (Idaho) sheet suggests a sedimentary series flanking an older mountain range. In reality, it consists of nearly horizontal lava flows resting unconformably upon a deeply eroded surface, above which the higher ranges form an unburied remnant. The relations, therefore, are essentially unconformable. The Flagstaff (Ariz.) sheet illustrates an almost opposite and still closely related type in which numerous volcanic cones have been built upon a comparatively level upland, with respect to which they are unconformable.

The previous examples indicate that structural unconformity as displayed on maps is apt to correspond to topographic unconformity. On the Cucamonga (Cal.) sheet the contrasted areas are a crystalline mountain range in early maturity and a depositional plain in the pre-erosion stage. The Lexington (Neb.) sheet shows an undissected flood plain bordered by areas probably in middle to late youth. The flood plain of the Elk Point (S. D.-Neb.-Iowa) sheet is wholly undissected, the inside terrace in very early youth and the upland areas perhaps in late youth or earliest maturity. Between a series of terraces such as those

on the Cohoes (N. Y.) sheet, it may be impossible to distinguish a difference in stage, although probably, in general, the higher areas should show the greater degree of dissection.

The difference may be one of character of the topography rather than stage, such as the contrast on the Indio special (Cal.) sheet (p. 201) or that between the belt of parallel ridges and the bordering highland on the Fort Collins (Colo.) quadrangle. Here both areas are probably in early maturity.

Topographic unconformity alone may, indeed, be very misleading, especially in regions showing peneplains, or stripped structural plains (pp. 111–121). For instance, the contrast between mountains and lowland on the Morgantown and Hickory (N. C.) sheets might easily suggest an unconformity. The lowland is perhaps in late youth, whereas the mountain areas are well not, early maturity. The character of topography is also misleadiing for the relief of the lowland is small, that of the mountains great. The drainage pattern is not distinctly different. Actually, the contrast merely represents the difference between an area formerly peneplaned but now considerably re-dissected, and the bordering unreduced highlands, and bears no relation whatever to unconformity.

The Mauston and Kendall (Wis.) sheets illustrate the contrast between an undissected plain recently perfected and the adjacent unreduced areas. The plain simulates old age, the unreduced remnant at the southwest is scarcely more than in late youth or early maturity, thus clearly illustrating topographic but not structural unconformity. There is probably, however, a considerable veneer of alluvium, which might be mapped as such. The alluvium, of course, is unconformable with respect to the older rocks below and in the highlands.

Topographic unconformity may sometimes be conditioned by a difference in rock hardness that coincides with structural unconformity. In this case partial peneplanation would be a true guide. An illustration is the Holyoke (Mass.) sheet, on which the highland that lies from 2 to 4 miles west of the Northamptom division of the New York, New Haven and

Hartford Railroad is composed of hard igneous and metamorphic rocks, the lowland along the railroad and eastward chiefly of softer unconformable Triaisic sandstone (Folio 50).

In conclusion, it seems that certain simple types of unconformities, particularly those between late unconsolidated deposits and older more or less dissected rocks which they partially or completely conceal, may readily be inferred from topographic maps. The evidence for certain other types, in which marked structural differences are present, is sometimes strongly suggestive, especially when one has some general knowledge of the region to assist in the interpretation. The less obvious types based mainly on missing beds or faunal breaks probably can seldom or never be recognized on topographic maps.

Probably, for the sake of completeness, one should include the unconformities between the deposits made by ice or by wind, and their underlying bedrock. The various types of glacial deposits may always safely be interpreted as unconformable upon the prevailing and usually more consolidated rocks beneath. Their thickness varies with the type of deposit (ground moraine, terminal moraine, drumlin, esker, etc.) from practically nothing to at most a few hundred feet. Maps are scarcely necessary for illustration.

Sand dunes, like most glacial deposits, by their method of formation imply deposition unconformably on a preexisting land surface. Like glacial deposits, they probably only rarely reach a thickness exceeding a few hundred feet, and are more commonly only a thin veneer.

Additional illustrations of certain well-known unconformities on topographic maps

Caddo Gap, Ark.
De Queen, Ark.-Okla.
Castle Rock, Colo.
Colorado Springs, Colo.
Denver double sheet, Colo.
Livermore, Colo.
Loveland, Colo.
Platte Canyon, Colo.
Granby, Conn.
Meriden, Conn.
New Haven, Conn.
Granville, Mass.-Conn.

Greenfield, Mass.
Northampton, Mass.
Springfield, Mass.-Conn.
Laurel, Md.
Relay, Md.
Saypo, Mont.
Canutillo, N. M.
Antlers, Okla.
Alikchi, Okla.
Lukfata, Okla.
Tishomingo, Okla.

APPENDIX TO PART I

LIST OF TOPOGRAPHIC MAPS USED IN PART I ARRANGED BY STATES

PART II

INTERPRETATION OF GEOLOGIC MAPS

THE NATURE OF A GEOLOGIC MAP

Maps

179. Pawpaw-Hancock folio, Md.-W. Va.-Pa.
196. Philipsburg folio, Mont.

The simplest type of geologic representation, known as an outcrop map, shows by pattern or symbol the actual outcrops of bedrock of the various formations, areas without exposures being left blank. A typical geologic map, however, shows, by means of colors or patterns, the distribution of rock formations, even where exposures are few or absent. If the mantle of soil is comparatively thin, this distribution is shown as it would be were the loose material completely stripped away, exposing bedrock. If the unconsolidated mantle is very thick, and seriously obscures the underlying geology, it may be mapped with a distinctive color or pattern of its own.

It should be understood from the outset that in most regions only a small proportion of the area occupied by any formation actually shows exposures (outcrops), a large part of the bedrock being buried more or less deeply by weathering products. Perhaps it is advisable here to call attention to the dual usage of the word *outcrop*, which in the restricted sense applies to an actual exposure of bedrock, and in a more general sense refers to the area where a formation occurs next beneath the soil, though not actually exposed to view. The context usually reveals the intended interpretation.

Of course, the colors and the patterns used in mapping are purely arbitrary, and have no relation to the color or the character of the rocks mapped. A definite scheme is now in use by the Federal Survey, so that a certain color is always reserved for the rocks of a given period. For instance, the Carboniferous is always shown in shades of blue, the various formations being distinguished by differences of pattern (Folio 196). The Federal color schedule is followed by many of the state geological surveys, but not by foreign surveys. Distinctive patterns are also used for sediments, for igneous rocks, and for metamorphics, explanations for which will be found at the top of each legend (Folio 196).

The legend of a geological map consists of a key to the color and pattern scheme, in which the sedimentary rocks are commonly arranged with the oldest at the bottom, and the igneous units grouped separately, without respect to their age relations to the sediments (Folio 196). In addition to the colors and the patterns, the initial letters of the period and the formation are generally used as an aid in identifying the beds on the map.

A formation, as the term is used in geological mapping, is a group of sedimentary beds sufficiently alike in lithologic character, fossil content, and relation to overlying and underlying beds, so that it is shown on the map as a unit. There may be, within a formation, a smaller unit sufficiently distinctive so that it is given a separate name as a member. A member is sometimes, but not commonly, shown in a separate color or pattern on the map. If it lies at the base or top of a formation, little confusion results, but if near the center, it will have the same rock above and below, and may cause some inconvenience in interpreting structure, as with the Parkhead sandstone member of the Jennings formation, on the Pawpaw quadrangle (Folio 179).

A geologic map is most useful when overprinted on contours, but may be placed on a flat base in areas where topographic maps are not available. A geologic map on a contoured base affords much more, and more definite, information than one on a flat base, but common sense and an understanding of how a geologic map is made are necessary, if one is to understand the limitations of quantitative results derived from such maps.

In the field, contacts are more often than not obscured by a soil cover; elevations are estimated with respect to houses, road corners, or other features not always accurately placed on the topographic base; thicknesses of formations actually vary from place to place; and, as a result, the map represents only the closest approximation to the facts that it is possible to get with a *reasonable* expenditure of time and money. On the average geologic map, a contact must not be expected to be closer than half a contour interval to its true elevation, and the error is often considerably greater. Where contours are badly crowded, this error is not uncommonly increased by the difficulty of clean-cut drafting of the contact lines.

The United States Geological Survey is preparing a geologic atlas of the entire United States, of which something over two-hundred folios have been issued to date. Each folio usually consists of a descriptive text, a topographic map, a geologic map showing the distribution of formations (the so-called areal or historical geology sheet, overprinted on the topographic base), a structural sheet showing structure sections across the area, and such economic geology sheets, artesian water sheets, and other special information as the character of the region may warrant. These folios afford the best material available for the study of geologic maps. Unfortunately, many of these are out of print, but they can be consulted in practically all college and technical libraries, and in the offices of many mining and oil companies and consulting geologists.

HORIZONTAL BEDS

SHAPE OF OUTCROP

Maps

33. Briceville folio, Tenn.
202. Eureka Springs-Harrison folio, Ark.-Mo.

Sedimentary rocks are ordinarily laid down in horizontal, or nearly horizontal, layers, resting on one another in the order of their age, the oldest at the bottom. It is obvious that if the rocks are strictly horizontal, and the topography perfectly

level, a single formation, the youngest in the region, will everywhere outcrop at the surface. As soon, however, as valleys are carved deeply enough to cut through the uppermost rock formation, a lower one will be exposed in the valley bottom; and if the valley is deep enough to cut through this unit, it will show as belts on the valley sides with a still older formation below. As the drainage develops and becomes typically dendritic (p. 101), the pattern of outcrop becomes very intricately branching, the contact planes between the horizontal formations intersecting the irregular topographic surface in lines that are coincident with, or roughly parallel to, the contours. The shape of outcrop of nearly horizontal beds in a much dissected country is especially well illustrated by the Eureka Springs-Harrison folio (No. 202). These sheets should be studied to gain an idea of how the formation contacts follow the contours along the drainage lines. The contrast between the dendritic pattern of horizontal or nearly horizontal rocks with the belted or linear pattern of highly folded and faulted areas is remarkably shown on the Briceville sheet (Folio 33).

Additional maps showing shape of outcrop in nearly horizontal beds

46. Richmond folio, Ky.
47. London folio, Ky.
53. Standingstone folio, Tenn.
119. Fayetteville folio, Ark.-Mo.
145. Lancaster-Mineral Point folio, Wis.-Iowa-Ill.
176. Sewickley folio, Pa.
178. Foxburg-Clarion folio, Pa.
200. Galena-Elizabeth folio, Ill.-Iowa.

THICKNESS OF BEDS

Maps

178. Foxburg-Clarion folio, Pa.

If a rock formation were strictly horizontal, its thickness could always be determined by the difference in elevation between its top and base, as shown by the contours. Since, however,

rocks are rarely, if ever, strictly horizontal, these elevations should be determined at closely adjacent points to eliminate the effects of even slight regional dip. For example, on the Foxburg-Clarion folio (No. 178), at the point where the twenty minute meridian crosses Clarion River, the top of the Pottsville formation (Cpv), is at about 1,400, its base at about 1,260 feet, a thickness of 140 feet. In the text of the folio, its thickness is given at from 120 to 130 feet. Inasmuch as an error of a contour interval is possible at each contact, in reading contours, and since additional errors in field mapping and drafting (pp. 14–15 and 217) enter into such a problem, this is as close a check as could possibly be expected.

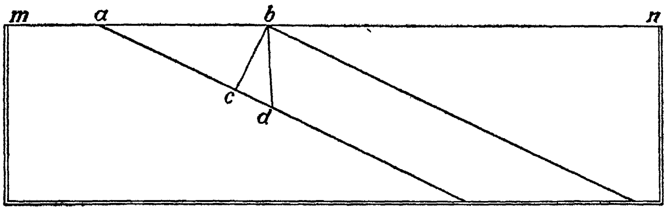


FIG. 14.—True and apparent thickness.

It should be noted that the elevations, in this determination, were taken over a very small horizontal distance. If, now, the elevation of the top be taken, at the point where the twenty minute meridian crosses Clarion River (1,400 feet), and that of the base where Mill Creek intersects the east edge of the map (1,380 feet), the apparent thickness is only 20 feet; whereas if the elevation of the base be taken where the twenty minute meridian crosses the river (1,260 feet) and that of the top at the east edge of the map (1,520 feet), the apparent thickness is 260 feet. This indicates clearly the necessity, even in regions of very low dip, of taking the elevations at very closely adjacent points to eliminate the effect of the inclination of the beds.

If the difference of elevation between top and bottom of a formation be taken exactly along the strike line, this method may be used with dips as high as 20°, without introducing serious

error. In Fig. 14, the bed *ab* outcrops on the surface *mn*, the angle of dip being *bac*. The line *bc* is the true thickness, and *bd* the apparent thickness, secured by difference of elevation of top and bottom of bed on the strike line. Angle *cbd* equals angle *bac* (the dip). In triangle *cbd* assume *bc* to be 100 feet, and the dip 10°. Then $bd = 101.5$ feet, a discrepancy of only 1.5 feet on a formation 100 feet thick. This is far within the limits of permissible error in map reading. With a dip of 20°, the apparent thickness of the 100-foot formation would be only 106.4 feet, which is also well within the limits allowable.

Of course, the larger the scale of the map and the smaller the contour interval—in other words, the more detailed the map—the more accurate the determinations will be. All the supplementary maps listed under the preceding section also serve as admirable examples from which to determine thickness of horizontal or nearly horizontal beds.

DIPPING BEDS

REGIONAL DIP

Maps

47. London folio, Ky.
53. Standingstone folio, Tenn.
61. Monterey folio, Va.-W. Va.
108. Edgemont folio, S. D.-Neb.
159. Independence folio, Kan.
197. Columbus folio, Ohio.
200. Galena-Elizabeth folio, Ill.-Iowa.
215. Hot Springs folio, Ark.

Rock beds, whenever they depart from horizontality, are said to have dip, which may be in any direction and any number of degrees. If the dip is low, and moderately uniform over a considerable area, as on the flanks of broad arches or geosynclines, it is said to be regional. If the regional dip is very low, and the dissection considerable, outcrops will have the typically dendritic pattern characteristic of horizontal rocks (Galena-Elizabeth folio, No. 200).

Not uncommonly, however, the regional dip is such as to give a moderately belted appearance to the map, still combined with the branching effect of horizontal beds. This is strikingly exhibited on the London (No. 47) and Standingstone (No. 53) folios, and should be contrasted with the far more perfect belting and absence of dendritic pattern of the highly folded regions represented on the Monterey (No. 61) and Hot Springs (No. 215) folios. As the regional dips become steeper, the belts become narrower and with less of the dendritic pattern of outcrop, a condition well illustrated on the Edgemont folio (No. 108). Even with low dips, the belts may be surprisingly regular, if the degree of dissection is as slight as that on the Independence folio (No. 159). In heavily glaciated regions, where outcrops are scarce, and boundaries much generalized, low regional dips are also associated with apparently regular belts of outcrop (Columbus folio, No. 197). Methods of determining the amount of regional dip are described on pages 236–242.

Additional maps showing typical areas of regional dip

22. McMinville folio, Tenn.
40. Wartburg folio, Tenn.
46. Richmond folio, Ky.
95. Columbia folio, Tenn.
107. Newcastle folio, Wyo.-S. D.
145. Lancaster-Mineral Point folio, Wis.-Iowa-Ill.
169. Watkins Glen-Catatonk folio, N. Y.
190. Niagara folio, N. Y.

SHAPE OF OUTCROP—RULES FOR "V's"

Maps

20. Cleveland folio, Tenn.
59. Bristol folio, Va.-Tenn.
61. Monterey folio, Va.-W. Va.
107. Newcastle folio, Wyo.-S. D.
160. Accident-Grantsville folio, Md.-Pa.-W. Va.
170. Mercersburg-Chambersburg folio, Pa.
174. Johnstown folio, Pa.
186. Apishapa folio, Colo.
193. San Francisco folio, Cal.

The shape of outcrop of regularly dipping beds on absolutely plane topography would be straight parallel belts. As soon, however, as these belts are carved by erosion, each valley produces a reentrant or crenulation in the outcrop, commonly termed a "V", and these "V's" constitute such an important item in map interpretation that they demand a very thorough study. They may be summed up as follows:

1. In horizontal rocks, the trace of the contact plane with the topography follows the contours (pp. 217–218), and, since these

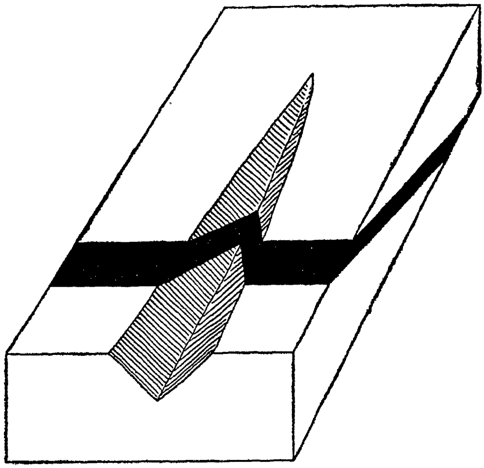


FIG. 15.—"V" produced by bed dipping upstream.

bend upstream, in crossing a drainage line, the "V" will point upstream, its length depending on the magnitude of the valley.

2. If the beds dip upstream (Fig. 15), the "V" will point upstream and in the direction of dip of the rocks.

3. If the beds dip downstream more steeply than the stream gradient (Fig. 16), the "V" will point downstream, and in the direction of rock dip.

4. If the beds dip downstream less steeply than the stream gradient (Fig. 17), the "V" will point upstream, and *opposite* to the direction of dip of the formations.

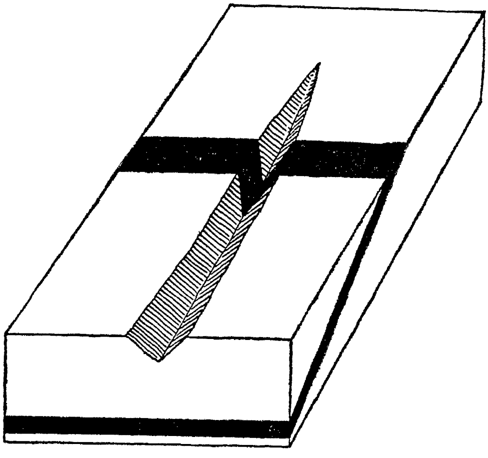


FIG. 16.—"V" produced by bed dipping downstream more steeply than stream gradient.

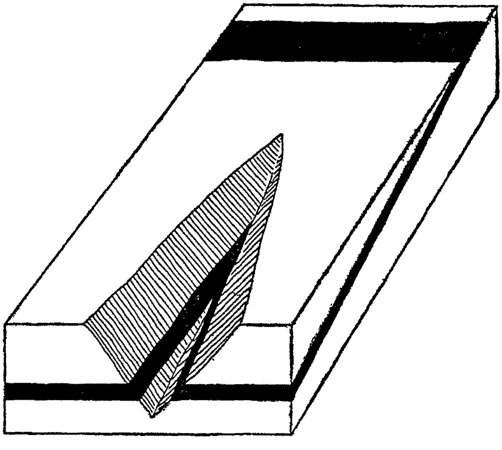


FIG. 17.—"V" produced by bed dipping downstream less steeply than stream gradient.

5. The "V's" will be infinity when rock dip and stream gradient have the same inclination; and as the dip increases beyond this point, the length of the "V's" decreases, becoming zero with vertical beds.

Perhaps the most outstanding feature of the above summary is the fact that in only one case do the "V's" point downstream, that is, where the beds are dipping downstream more steeply than the stream gradient. Therefore, all "V's" that point downstream give absolute evidence of the direction of rock dip. This statement may be depended on as an invariable rule.

It will be noted also that there is only one case in which the "V" does *not* point in the direction of dip. This occurs only when the beds dip downstream less steeply than the stream gradient. To appreciate the significance of this exception, it must be remembered that few streams of any considerable size have gradients exceeding 50 feet to the mile, and most rivers do not exceed 10 or 15 feet. Beds, therefore, that dip downstream more gently than the stream gradient of any large creek or river are essentially horizontal.

Since beds do not usually show appreciable parallel or linear outcrop, unless the dip is several degrees (a degree is about 90 feet to the mile), one may safely conclude that on a map in which the outcrops are belted all "V's" on the larger streams point in the direction of dip, and it is only on the steeper headwater tributaries that the exception occurs of "V's" that point in the opposite direction.

If beds are vertical, there are, of course, no "V's" where the streams cross the contacts between formations. It must not be inferred from this, however, that the absence of "V's" where a stream crosses such a contact proves vertical beds. There are several reasons why such an inference would be unsafe: (1) If the stream has no appreciable valley, no crenulation will be formed. A moment's thought should make it perfectly obvious that it is the valley, not the stream, that is responsible for the reentrant. Even though no permanent stream occupies the valley, the rules for "V's" still hold perfectly. (2) On many of

the older maps careless field work or a failure to appreciate the importance of the "V's" has resulted in their omission, unless they were perfectly obvious in the field. Consequently, on certain of the older maps the absence of "V's" has little structural significance. On the contrary, in the best modern mapping, many "V's" are shown where outcrops are sparse or entirely lacking, the "V's" being drawn by inference from the known structure. (3) The "V", though actually present in the field, may be so short that it cannot be shown on the scale of the map. To appreciate the great importance of this point, let us assume a case of beds dipping 45°, and a valley of moderate depth, say 200 feet. With beds inclined at 45°, a valley 200 feet deep will produce a "V" 200 feet in length. On an inch-to-the-mile scale ($1/62,500$), 200 feet will show as $200/5,280$, or about $1/25$ inch. On a map with the scale of $1/2$ inch to the mile ($1/125,000$), the same "V" would only be $1/50$ inch long. As the dips become steeper, the "V's" become even less conspicuous, so that the absence of "V's", even on modern well-made maps, does not necessarily indicate vertical beds, but only very steep dips.

Remarkably fine examples of the "V's" produced by beds dipping downstream more steeply than the stream gradients are to be found on the northeast third of the Apishapa quadrangle (Folio 186), along the contact between the Carlile shale (Kcr) and the Timpas limestone (Kt), also between the Timpas limestone and the Apishapa shale (Ka). The many streams that cross these contacts are flowing northeast, and the apex of each "V", where it rests on the stream line, points northeast. The student, however, must guard against becoming confused by the fact that on each divide between two closely adjacent streams there is also a "V" pointing in the reverse direction, as, for instance, in the contact between the Graneros shale (Kgs) and the Greenhorn limestone (Kg) on the divide between Mustang Creek and Peterson Canyon (N. cent. rect., Apishapa quadrangle), where the "V" that has its apex on the ridge points southwest. On each of the valleys mentioned, however, there is a "V" in the same contact that points northeast *downstream*, the

apex of the "V" resting on the stream line. These are the "V's" that indicate the direction of dip. Where the mapping has been well done, the "V's" formed on ridges are not commonly as sharp-pointed as those in the valleys.

Striking examples of "V's" pointing downstream are also to be seen in the south central rectangle of the Grantsville quadrangle (Folio 160), along the contact between the Jennings (Dj) and Catskill (Dck) formations, where the reversed "V's" on the divides are also shown.

In the same rectangle, there is a very conspicuous "V" in the contact between the Catskill (Dck) and Pocono (Cpo) formations along Savage River. The beds are dipping downstream more steeply than the stream gradient, the "V" is pointing downstream and in the direction of dip of the rock beds. Just south of Bear Hill (E. cent. rect., Grantsville sheet), the same beds occur dipping in the same direction (southeast), but here the stream flows in a direction opposite to Savage River, and we have an excellent illustration of the case in which the beds dip upstream, with the "V" pointing upstream and in the direction of rock dip. Several other illustrations of beds dipping upstream occur along the contact between the Catskill and Pocono formations in the southwest rectangle.

Beds dipping downstream more steeply than the stream gradient are also well illustrated on the Monterey quadrangle (Folio 61). On Michael Mountain (W. cent. rect.) the "V's" point downstream on the numerous small streams flowing away from the crest, on both sides; the same is true of Boler Mountain (SW. rect.); whereas on Monterey Mountain (NE. rect.) the "V's" point downstream on the east side of the crest, while the few very small "V's" on the west slope illustrate beds dipping upstream, the "V's", consequently, pointing upstream and in the direction of dip.

The case of beds dipping upstream is also well shown on the Bristol quadrangle (Folio 59), particularly on the northwest flank of Moccasin Mountain (W. cent. and cent. rects.), and on the northwest flank of Copper Ridge (W. cent. and N. cent. rects.).

The two cases just illustrated may be studied to advantage on many other folios of the Rocky Mountain and Appalachian Mountain regions.

It has already been pointed out (p. 224) that beds dipping downstream less steeply than the stream gradient are most common in the steep headwater branches of drainage systems. There they often produce a unique result, owing to the fact that as the gradient of the stream, which in its headwaters is steeper than the dip of the beds, becomes flatter in the lower reaches, it also becomes less than the dip of the formations. In this way

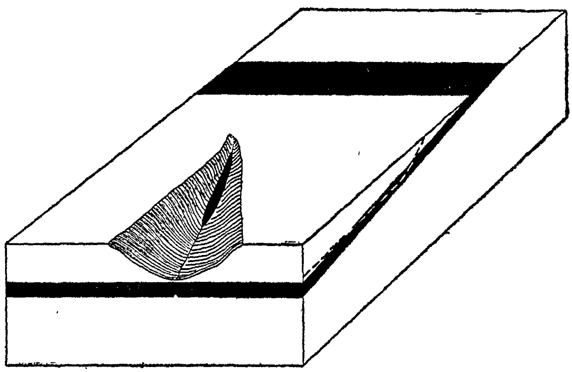


FIG. 18.—"Window" caused by change in stream gradient.

we have in the upper reaches of the stream the beds dipping downstream less steeply than the stream gradient, whereas farther downstream, merely as a result of the decrease of gradient, the beds dip downstream more steeply than the stream gradient, although the dip has remained constant in direction and amount. This may be seen quite clearly by reference to Fig. 18, in which the solid black is the dipping bed, and the dotted line in the edge of the block is the projection of the stream gradient, which in its upper course is steep enough to cut down through the black band, and in its lower course becomes flatter than the dip.

In this manner we have two "V's" pointing in opposite directions, forming a "window" through which an inlier of an older

formation shows. Though such a "window" is almost invariably interpreted as the result of an anticline, the diagram (Fig. 18) shows clearly that it can be produced on beds dipping in only one direction and at a constant angle, the variable being the gradient of the stream.

An obvious case of this sort occurs on the Newcastle quadrangle (Folio 107), producing the fishhook-shaped inlier of Lakota sandstone (Klk) in the midst of the Dakota (Kd) in the southwest corner of T. 5 S., R. 1 E. At the northeast tip of the inlier, the beds are dipping downstream less steeply than the stream gradient, the "V" pointing upstream and opposite to the direction of dip. At the southwest tip of the same inlier, the beds are dipping downstream more steeply than the stream gradient, the "V" pointing downstream in the direction of dip. The difference results not from change in dip, the inclination of the beds being very nearly constant, but from the change in stream gradient. Several similar cases occur in the west half of T. 46 N., R. 62 W., and at other points on the Newcastle quadrangle.

Inliers of similar appearance may be formed where streams cross an anticline. Where the Conemaugh River crosses Laurel Ridge (Johnstown folio, No. 174) such an inlier of the Catskill formation (Dck) is exposed. Here, however, it is obvious, from the changing elevation of the contact of the Catskill with the overlying Pocono (Cpo), that the structure is anticlinal, the elevation of the contact being higher near the center of the inlier by some hundreds of feet than at either end. On the other hand, in the case cited on the Newcastle sheet, the contact, as shown by the contours, is descending at a uniform, or nearly uniform, rate in one direction, and there is not the slightest evidence of anticlinal structure.

The inlier of Catskill on the Johnstown sheet illustrates two cases of "V's". At the northwest end the beds dip downstream (northwest) more steeply than the stream gradient; therefore, the "V" points downstream and in the direction of dip. At the southeast end the beds dip upstream (southeast); hence, the "V" points upstream and in the direction of dip.

There are numerous illustrations on geologic maps of streams crossing the contact of dipping beds without any "V" being shown. A striking example occurs in the northwest corner of the Cleveland sheet (Folio 20), where Tennessee River crosses the belt of Chickamauga limestone (Sc). There may be several possible explanations. First, it will be noted that there is no conspicuous valley, and it takes a valley, rather than merely a river, to produce a "V". In the second place, this is an old map, and was probably not made with as keen an appreciation of the value of "V's" as we now have. In the third place, the beds may be so steep (though not necessarily vertical) that the "V" is too short to show on this small-scale map. Many similar cases occur on this sheet. It would probably be unsafe to interpret them all as indicating vertical, or even nearly vertical, beds, though the dips are, for the most part, undoubtedly steep.

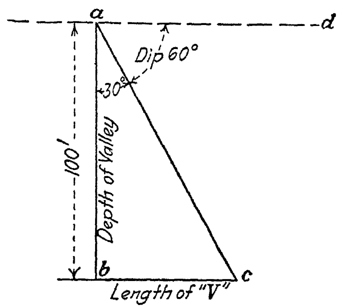


FIG. 19.—Solution for length of "V".

On the Mercersburg quadrangle (Folio 170), Campbell Run crosses the outcrop of the Chambersburg limestone (Oc) (E. cent. rect.) in a valley less than 100 feet deep, where the dip is 60°, and no "V" is shown, though, in general, the mapping appears to be carefully done. In Fig. 19,

$$\begin{aligned} \text{Let } dac &= \text{the dip, } 60°\text{, and} \\ ab &= \text{vertical depth of valley, 100 ft.} \\ \text{Then } \angle\, bac &= 30°\text{, and} \\ \tan 30° &= \frac{bc}{100}; \\ \text{Whence } bc &= 58 \text{ ft., the length of the "V".} \end{aligned}$$

On the inch scale, this "V" would be only slightly over 0.01 inch long, which is practically inappreciable. There are enough carefully executed "V's" to indicate that this one was not omitted

through carelessness, and we must conclude, as already pointed out (pp. 224–225), that the absence of "V's" on the newer maps means steep, though not necessarily vertical, dips.

On the Concord quadrangle (Folio 193) are conspicuous examples of the absence of "V's", for the most part associated with dips ranging from 45 to 90°.

Additional maps illustrating the shape of outcrop in dipping beds, and the rules for "V's"

78. Rome folio, Ga.-Ala.
85. Oelrichs folio, S. D.-Neb.
93. Elkland-Tioga folio, Pa.
108. Edgemont folio, S. D.-Neb.
127. Sundance folio, Wyo.-S. D.
141. Bald Mountain-Dayton folio, Wyo.
142. Cloud Peak-Fort McKinney folio, Wyo.
175. Birmingham folio, Ala.
179. Pawpaw-Hancock folio, Md.-W. Va.-Pa.
215. Hot Springs folio, Ark.

FACTORS DETERMINING THE WIDTH OF OUTCROP

Maps

20. Cleveland folio, Tenn.
33. Briceville folio, Tenn.
Rolla quad., Mo. Bur. Geol. and Mines, 2nd ser., vol. 12.

The width of outcrop of any given formation is controlled by three factors: (1) the thickness of the formation, (2) its angle of dip, and (3) the slope of the topography.

1. Formations vary in thickness from place to place, and it is quite obvious that, other factors being equal, the thicker formation will have the wider outcrop. The variation in thickness of a single formation from place to place may sometimes, though not as a rule, be sufficient to make a striking, or at least appreciable, difference in the width of outcrop, but more often the difference, within the limited area of a single map, is due to one or the other of the two remaining factors.

2. Dip of beds is an important factor in the width of outcrop. On perfectly plane horizontal topography, a horizontal bed will be limited in outcrop only by the lateral extent of the formation itself. As the dip increases, the width of the outcrop decreases, and when the bed is vertical is equal to its thickness. This will be made clearer, perhaps, by a reference to Fig. 20. Since the dip may change rapidly from place to place, this is an important factor in interpreting structure from geologic maps. The elliptical outcrop of Tellico sandstone (St) in the central and northeast rectangles of the Cleveland sheet (Folio 20) is an excellent illustration. The narrower outcrop on the southeast flank

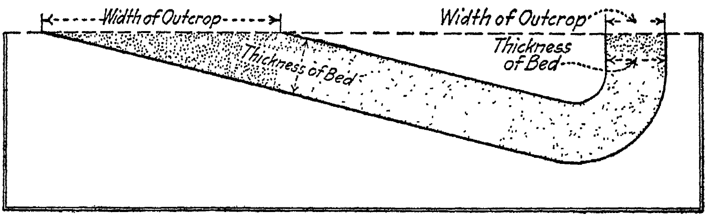


Fig. 20.—Relation of dip to width of outcrop.

is, obviously, the result of steeper dip, since on both belts there are points where the topography is essentially horizontal.

3. If the beds are horizontal, the slope of the topography is, very obviously, the chief control in the width of outcrop. With horizontal topography, a horizontal bed, as stated above, will outcrop over an area coextensive with the lateral development of the bed itself. If, on the other hand, the bed outcrops in the face of a vertical cliff, its *width of outcrop* is zero, as represented on a map. There are all possible variations between these limits. The principle may be clearer from an inspection of Fig. 21. It is well illustrated on the Rolla quadrangle (Mo. Bur. Geol. and Mines, 2nd ser., vol. 12). In sec. 33, T. 36 N., R. 8 W., the Roubidoux sandstone (R) has a narrow outcrop, owing to steep slopes. In secs. 21 and 22 of the same township, where the thickness is almost exactly the same, the width of outcrop is

considerably greater, owing to the gentler topographic slopes. The varying width of outcrop of the Wartburg sandstone in the west central rectangle of the Briceville sheet (Folio 33) results chiefly from the same cause.

It is very unusual for an entire formation to outcrop in the face of a perfect cliff, and, when it does so, the best mapping practice is to exaggerate the width so as to show it at least by a line, in order to avoid the incorrect impression that the bed is missing.

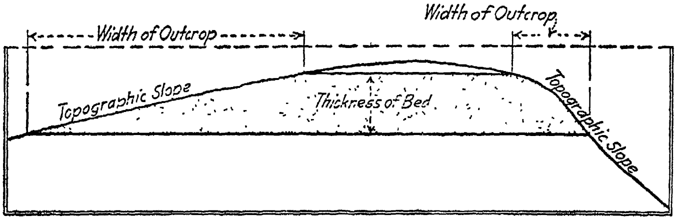


FIG. 21.—Relation of slope of topography to width of outcrop.

All possible combinations of angle of dip and slope of topography may enter into the problem of width of outcrop. A true conception of their combined effect is fundamental to any real comprehension of structure as deduced from maps (see also pp. 243–259).

DETERMINATION OF STRIKE

Maps

47. London folio, Ky.
186. Apishapa folio, Colo.
200. Galena-Elizabeth folio, Ill.-Ia.
215. Hot Springs folio, Ark.

Strike may be defined as the intersection of a dipping plane with a horizontal surface. The dipping plane may be the top, the bottom, or any other definitely identifiable plane, of a formation. On a map, however, the top and the bottom of a bed are usually the only surfaces that can be positively recognized. By

the bottom of the bed is meant its contact plane with the next older bed; the top, with the next younger formation. Normal contacts should be chosen. Present erosion surfaces are of no value, naturally, and even unconformable contacts (p. 331) are to be avoided, so far as possible.

Since, on a topographic map, any contour represents a horizontal plane, strike may be determined by finding the intersection of a contact plane with any contour.

In the northeast third of the Apishapa quadrangle (Folio 186), for example, the contact plane between the Timpas (Kt) and Apishapa (Ka) formations intersects the 4,800-foot contour at numerous points. If these points are connected on the map by a series of short, straight lines, they are all seen to have the general direction of about N. 45° W., which represents the regional strike.

A careful inspection of these short lines will show that they do not make one single straight line, but vary slightly in bearing. This may result from two causes: First, there may be slight inaccuracies in mapping the intersection of the contour with the contact. In so far as these are the cause of the discrepancy, the longer the line chosen the more accurate the resulting strike, since a few feet error intercepts a smaller angle at 10 miles than at 1 mile. On the other hand, there may be actual slight variations of strike, throughout the distance across the sheet, due to unequal warping of the rocks. The length of line chosen will depend, therefore, on whether regional or local strike is desired. Judgment in a matter of this sort comes only with experience.

It will be noted that in the northeast portion of the Apishapa quadrangle the bands of formation run essentially parallel to the determined strike, and it may be inferred at once that these bands give the strike, without the use of contours. Such an inference is usually approximately correct, but it is often wise to check it by the method described above.

On the London quadrangle (Folio 47) it is considerably more difficult to determine strike, chiefly because the rocks are much more nearly horizontal, the contact planes and contours more

nearly parallel, and their points of intersection, consequently, much harder to determine precisely. To appreciate this, use the base of the Newman limestone (Cn) as a datum plane, and locate points of intersection with the 1,000-foot contour. The result will be a large number of short lines in a variety of directions, but a generalized line through them all will show about the same bearing as a long line drawn through the southernmost and northernmost of the intersection points, namely, about N. 30° E. If viewed from a distance, the map will show a rude banding, having about the bearing of the computed strike. The banding is more obscured by dendritic outcrop pattern than on the Apishapa sheet, because the rock formations are more nearly horizontal, under half a degree on the London sheet, about 2° on the Apishapa.

Another method of finding the strike on a uniformly dipping plane is shown in Fig. 22. Let *a*, *b*, and *c* be any three points not in the same straight line, on a given contact. Find the elevation of these points, either from the contours or from bore holes. Let us assume that *a* is 800 feet, *b* 1,050 feet, and *c* 900 feet. Connect the points by straight lines, forming the triangle *abc*. At some point along *ab*, the contact will have the same elevation as at *c*, that is, 900 feet. Since the drop from *b* to *c* is 150 feet, and that from *b* to *a* 250 feet, the desired point will be 3/5 (150/250) of the distance from *b* to *a*. Therefore, divide *ab* into five equal parts. At a point *d*, three of those parts from *b*, the elevation of the plane will be 900 feet, just as at *c*. Consequently, *cd* is the strike of the dipping plane.

On the Elizabeth quadrangle (Folio 200), the base of the Niagara (Sn) near the center of the SE. 1/4 sec. 12, T. 27 N., R. 3 E. is about 1,050 feet (point *b* of Fig. 22); near the center of the E. 1/2 sec. 9, T. 26 N., R. 3 E., the same contact is at 800 feet (point *a* of Fig. 22); and near the center of the NE. 1/4 sec. 4, T. 26 N., R. 4 E., it is at 900 feet (point *c* of Fig. 22). Draw lines on the map, connecting these points, and they will fully reproduce Fig. 22. The drop from *b* to *c* is 150 feet, that from *b* to *a* is 250 feet. There will be a point on *ab* having the eleva-

tion of *c*, and it will be $^{150}/_{250}$ ($^3/_5$) of the distance from *b* to *a*. Locate this point, call it *d*, and draw *cd*, the desired strike. There is also, of course, a trigonometric solution for this problem, but the graphic solution is much simpler and sufficiently accurate for all map-reading purposes.

In more highly folded areas, such as the Hot Springs quadrangle (Folio 215), the trend of the belts may be depended on

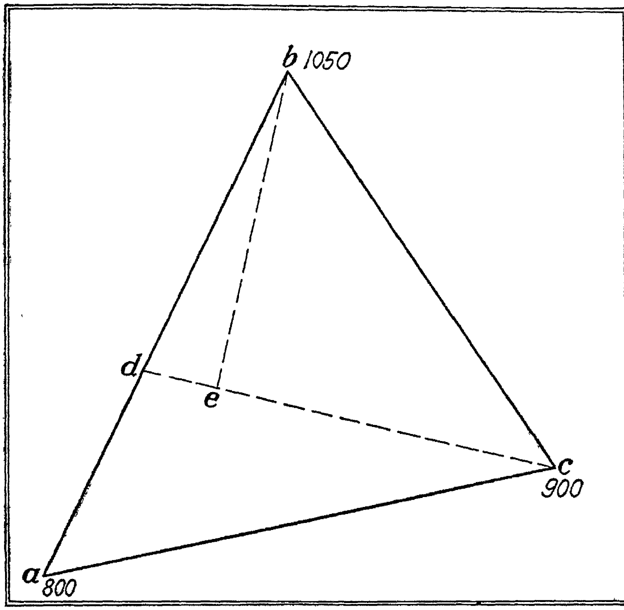


FIG. 22.—Solution for strike and dip, with three elevations given.

directly to give the strike, though this may be checked if desired by the same methods used above. Of course, in a folded area, all observations must be taken on a single flank of the fold, as it is obvious that the beds, except at the end, cannot possibly strike across the axis of the fold.

For additional maps illustrating strike, see the lists for regional dip (p. 221) and shape of outcrop in dipping beds (p. 230).

DETERMINATION OF DIP

Maps

47. London folio, Ky.
60. La Plata folio, Colo.
107. Newcastle folio, Wyo.-S. D.
142. Cloud Peak-Fort McKinney folio, Wyo.
170. Mercersburg-Chambersburg folio, Pa.
186. Apishapa folio, Colo.
197. Columbus folio, Ohio.
200. Galena-Elizabeth folio, Ill.-Iowa.

Dip may be defined as the maximum angle that a dipping plane makes at the given point with the horizontal. The vertical plane in which this angle lies must, by well-known geometric principles, be normal to the intersection of the dipping plane with the horizontal, that is, normal to the strike.

Any three points on a dipping plane, if they are not in a straight line, are sufficient to determine its strike and dip. This method of working out strike is illustrated in Fig. 22 (p. 235). Assuming the strike to be solved in the given problem (Fig. 22), drop *be* from *b* normal to the strike line *cd*. Then the bed inclines 150 feet in a distance *be*, which may be scaled from the map (Folio 200). In the problem on pages 234–235 this distance is 3.75 miles, a drop of 150 feet in 3.75 miles or about 40 feet to the mile. Of course, the same problem can be solved by trignometric methods, but the graphic solution is much simpler, and is sufficiently accurate for all geologic purposes.

If, on any regularly dipping contact plane, two points be chosen, in a line at right angles to the strike, the difference in elevation between the two is a measure of the dip of the formations. Going back to the London folio (No. 47), let us use the base of the Newman limestone (Cn) as our contact plane. The strike has already been determined (pp. 233–234) and the reference line *A-A* is essentially normal to it, so that points along it will satisfy the requirement that elevations must be chosen in a line normal to the strike

At the westernmost point where *A-A* crosses the basal contact of Cn, the elevation is about 1,225 feet. At the easternmost point where *A-A* crosses the same contact, the elevation is about 975 feet. The drop is, therefore, about 250 feet in a distance of about 7 miles, or approximately 35 feet to the mile, a little more than one-third of a degree.

Since it is of the utmost importance to engineers to know the degree of accuracy to be expected in the various phases of their work, it may be well to check this figure. For this purpose, let us take the top of the Pennington shale (Cpn) as a datum plane. At the north end of the ten minute meridian its elevation is about 1,350 feet. An inch and a half north of the east end of the twenty minute parallel the same contact is at about 950 feet. These two points determine a line nearly normal to the strike. The drop is about 400 feet in about 12 miles, or 33 feet to the mile.

The check is even closer than one would have any right to expect. Let us compare it with a figure from the south part of the map, using the base of the Pennington shale (Cpn) on the reference line *B-B*. At the westernmost place where this contact crosses *B-B*, the elevation is about 1,100 feet; at the easternmost, about 850 feet (difficult to read), a drop of 250 feet in about 8 miles, or 31 feet to the mile. The close check in these figures indicates that the regional dip in this area is very regular. The possible sources of error in a computation of this type may be briefly summed up as follows:

1. It is not possible to read the exact elevations where the contours are badly crowded, so that errors as great as a contour interval in each reading may be possible, that is, two intervals in a dip determination. With a large interval, such as 50 or 100 feet, this might introduce a considerable error, which, of course, will be reduced in importance as the distance between the two points is increased. That is, a 200-foot error in a mile is serious, whereas in 10 miles the error reduces to 20 feet to the mile. Naturally, with more detailed maps and smaller contour intervals this error becomes of less moment.

2. The two points may not be chosen in a line normal to the strike. However, a departure from the normal up to 10° is easily within the limits of allowable error in a problem of this kind. This may be seen by a study of Fig. 23.

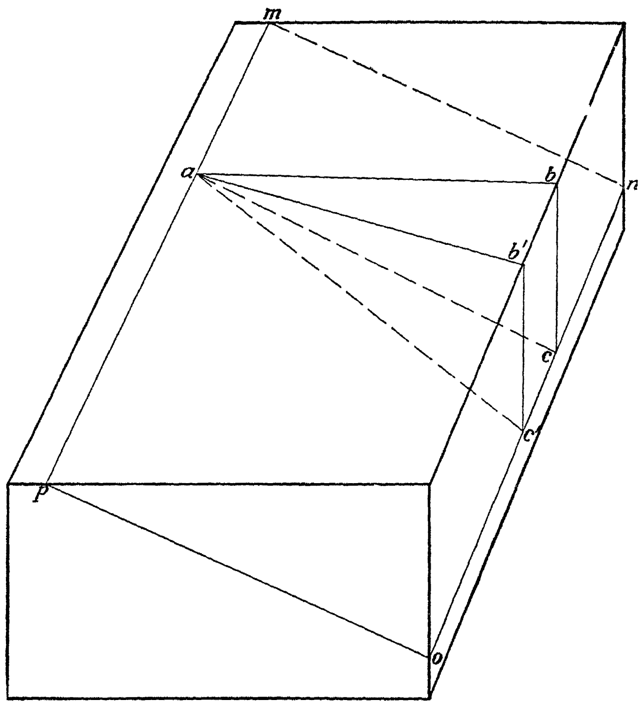


FIG. 23.—Variation in angle between true dip and dips in other directions.

In this figure *mnop* is a dipping bed, *mp* being the strike line, and *ab*, normal to *mp*, the direction of dip. Angle *bac* is the angle of dip. Angle *b'ac'* is another plane angle varying 10° from normal to the strike, that is, angle *bab'* is 10°. It is obvious that *bc* and *b'c'* are equal, but, since *b'c'* is farther from *a* than *bc*, that is, *ab'* is longer than *ab*, then *b'c'* subtends a smaller angle than *bc*.

In rt. $\triangle\ abb'$, $$\cos \angle bab' = \frac{ab}{ab'}. \tag{1}$$

Then $$ab' = \frac{ab}{\cos \angle bab'}. \tag{2}$$

In rt. $\triangle\ abc$, $$\tan \angle bac = \frac{bc}{ab}. \tag{3}$$

In rt. $\triangle\ ab'c'$, $$\tan \angle b'ac' = \frac{b'c'}{ab'}. \tag{4}$$

Since $bc = b'c'$, $$\tan \angle b'ac' = \frac{bc}{ab'}. \tag{5}$$

Substituting from Eq. (2), $$\tan \angle b'ac' = \frac{\frac{bc}{ab}}{\cos \angle bab'}. \tag{6}$$

Simplifying, $$\tan \angle b'ac' = \frac{bc}{ab} \cdot \cos \angle bab'. \tag{7}$$

Substituting from Eq. (3), $$\tan \angle b'ac' = \tan \angle bac \cdot \cos \angle bab'. \tag{8}$$

Now with a dip of 3° and a departure from normality to strike line of 10°, Eq. (8) becomes

$$\tan \angle b'ac' = 0.0524 \times 0.9848 = 0.0516, \text{ and}$$
$$\angle b'ac' = 2° \ 57'.$$

In other words, a dip which is actually 3° will be read as 2° 57′, by choosing a line of observation as far as 10° from normal to the strike. The formula shown is perfectly general, and the error for any dip and any amount of departure from normality to strike can be determined in a few moments by its use.

3. These three dips were taken on three separate horizons, and although each may be absolutely correct for the bed used, they may vary somewhat, owing to thinning or thickening of one or more beds, so that the upper surface of one bed may not be parallel to the upper surface of another.

4. The beds may be warped unevenly, so that the amount of dip changes from place to place. The greater the distances between elevations the more nearly average will the figure be, though it may entirely fail to show important local variations. The shorter the distances the more nearly will the result reflect

local conditions, provided the map is sufficiently detailed to make close reading of the contours possible.

The method developed above is most readily applicable in considerably dissected regions of low dip. A further example might be cited on the Galena-Elizabeth folio (No. 200). The base of the Maquoketa shale (Om) may be taken as a contact plane. Locate the points on the Elizabeth sheet where this intersects the 900-foot contour. These, when connected, show much local variation in direction, but may be represented on the whole by a line about N. 45° W., the average regional strike.

In the NW. cor. sec. 25, T. 28 N., R. 3 E., this contact is at 900 feet; near the center of sec. 35, T. 27 N., R. 2 E., it is at 700 feet, a drop of 200 feet in 9½ miles, or about 21 feet to the mile. The two points chosen form a line nearly normal to the strike. At the center of sec. 7, T. 27 N., R. 4 E., the elevation of this same datum is 900 feet; and in the NW. ¼ sec. 2, T. 26 N., R. 3 E., it is 725 feet, a drop of 175 feet in 5 miles normal to the strike, or about 35 feet to the mile. The close spacing of the structural contours (pp. 324–330) shows that the dip is somewhat steeper in the second case than in the first, and both determinations indicate a very low regional dip.

A slight modification of this method may be used in many areas where the dip is somewhat steeper, as on the Apishapa sheet (Folio 186). Mustang Creek (N. cent. rect.) affords a good example, using the contact between the Carlile shale (Kcr) and the Timpas limestone (Kt) as the datum plane. The intersection of this plane with the 5,100-foot contour gives the local strike as about N. 60° W. The elevation of the contact at the apex of the "V" is about 4,815 feet, or a drop of 285 feet between the apex and the 5,100-foot strike line. The distance, determined by a normal from the tip of the "V" to the given strike line, is found by measurement to be about 1.9 miles, or a dip of 150 feet to the mile, which is equal to about 1½°. This method is applicable to all "V's" that are long enough to make map measurements practicable, though, naturally, the shorter the "V" the higher the percentage of error.

On Saunders Arroyo (same rect.), the strike line may be determined where the 5,100-foot contour crosses the same contact, and is about N. 35° W. The apex of this "V" is at about 4,875 feet, a drop from the determined strike line of 225 feet in a distance measured *normal* to the strike of about 1.1 miles, or a dip of 205 feet to the mile, which is a little over 2°.

Along Apishapa River (E. cent. rect.) the intersection of the same contact with the 4,900-foot contour determines a strike line about N. 55° W. The apex of the "V" is at about 4,715 feet, or a drop of 185 feet in a distance normal to the strike of 1.2 miles. This gives a dip of 154 feet to the mile, again about 1½°.

In all of the above cases, the contours are clear and easy to read, and the results probably as accurate as the field mapping on which they are based. The apparent discrepancies are, undoubtedly, the result of actual changes of dip, and may be depended on to within a few feet per mile.

Attention has been called (p. 225) to the fact that on the divides between closely adjacent streams there may be salients in the outcrop, resembling the normal "V's" but pointing in the opposite direction. These, of course, may also be used in getting the amount of dip. A good example occurs at the base of the Dakota sandstone, in the southwest corner of T. 5 S., R. 1 E., on the Newcastle folio (No. 107). The intersection of the base of the Dakota sandstone (Kd) with the 4,000-foot contour determines the strike to be about N. 30° W. The elevation of the same contact at the apex of the reversed "V" is about 4,700, or a rise of 700 feet. The distance must, as before, be a normal from this apex to the given strike line, and is about 1.4 miles, the dip being 500 feet to the mile, or about 5.4°.

Incidentally, it may be worth while here to call attention to the fact that for the first 6 or 8° the tangent of an angle varies nearly in proportion to the angle. A dip of 1° means a drop of 92.4 feet per mile. A dip of 6°, for all practical purposes in map interpretation, may be considered as 6×92.4 feet. Dividing 500 by 92.4 gives a result of 5.4° (5° 24′), whereas actual use of

tables shows 500 feet to the mile to be equal to 5° 25′. The resulting error of 1′ is wholly negligible in map reading.

In the southwest portion of the La Plata folio (No. 60) the contact of the Mancos shale (Kmc) and Mesaverde formation (Kmv) intersects the 8,000-foot contour in a strike line bearing about N. 70° W. The apex of the "V" on Cherry Creek is at about 7,100 feet, or a drop of 900 feet in 3.6 miles, measured normal to the strike. This is equivalent to an average of 250 feet per mile, or 2.7°. Within the area involved, the dips recorded are 10, 8, 6, and 5°. Again, on La Plata River the intersection of the same contact with the 8,700-foot contour gives an east-west strike. The apex of the "V" is at about 8,125 feet, or a drop of 575 feet in a distance of 1.9 miles. This is equivalent to 303 feet per mile, or nearly 3⅓°. Within the area of the determination, the figures recorded are 8, 12, 15, and 10°. It would seem rather clear that the man in the field recorded the more obvious dips—in other words, those distinctly above the average —giving a highly misleading idea of the actual amount of dip throughout the area as a whole, though his figures are probably correct for the immediate locality of the observation.

On the Cloud Peak quadrangle (Folio 142) the triangular outcrop of the Madison limestone (Cm) in the central and west central rectangles at Ed Point affords a favorable opportunity to check the same thing. The intersection of the base of the Madison with the 8,500-foot contour gives a strike about N. 35° W. At the northeast apex of the triangle (or "flatiron") the same contact is at 9,400 feet, a rise of 900 feet in 1¾ miles, or 514 feet per mile, equivalent to about 5½°. The recorded dip is 8°.

On the outlier of Madison between Canyon Creek and Onion Gulch (S. cent. rect.), the strike is about the same as above. At the northeast end of the outlier the elevation is 8,700 feet; at the southwest end 7,300, a drop of 1,400 feet in 2.7 miles, which is 519 feet per mile, or about 5⅗°, whereas the recorded figure is 13°. Again the recorded dips do not represent average figures, but are distinctly local. This fact is worth keeping in mind in reading geologic maps.

With much steeper dips, the "V's" commonly are so short that two points on the same contact, in a line at right angles to the strike, cannot be located. It then becomes impossible to determine the dip from the map, unless the thickness of the formation is known. Where the thickness is known, the dip may be worked out as follows:

In Fig. 24 *A*, the formations *a*, *b*, and *c* are dipping eastward, as shown by the "V's", which, however, are too short to allow of computing dip. Points *m* on the base of *b* and *n* on the top of *b* are chosen in a line normal to the strike. If the topography

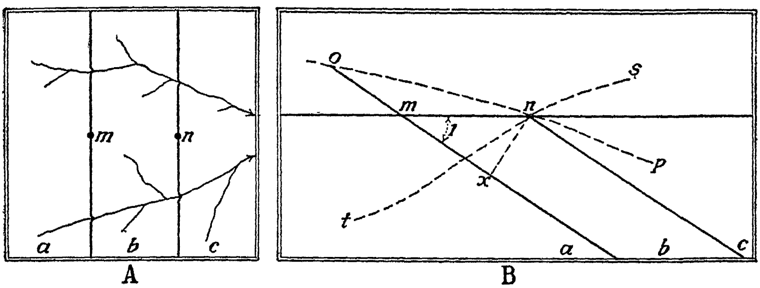


FIG. 24.—Solution for dip, thickness given, horizontal topography.

is horizontal, the problem is very simple. Figure 24 *B* is a cross-section through *mn*, at right angles to the strike, showing *a*, *b*, and *c* dipping east. The line *mn* is the horizontal topography, the distance being scaled from the map and *reduced to feet.* The line *nx* is the thickness of formation *b*, which must be known. Then $\sin \angle 1 = \frac{nx}{mn}$, or, expressed in general terms, the thickness of the bed divided by the width of its outcrop, gives the sine of the angle of dip, which is then determined from a table of natural functions.

In order to show the conditions where the topography is not horizontal, two other topographic surfaces have been sketched in Fig. 24 *B* as dotted lines *op* and *st*, from which it will at once

be seen that the width of outcrop varies with the topographic slope, and cannot be used as a direct factor, unless both contacts are at the same elevation.

In Fig. 25 *A*, the conditions are the same as before, except that m is at an elevation of 500 feet and n at 300 feet, the topography sloping east with the dip of the beds. Figure 25 *B* is again a cross-section through mn, the line mn now representing an inclined topographic surface. Through m draw mk horizontal, and through n draw nk normal to mk. Again, nx is the given thickness of bed. The distance from m to n, scaled on the map,

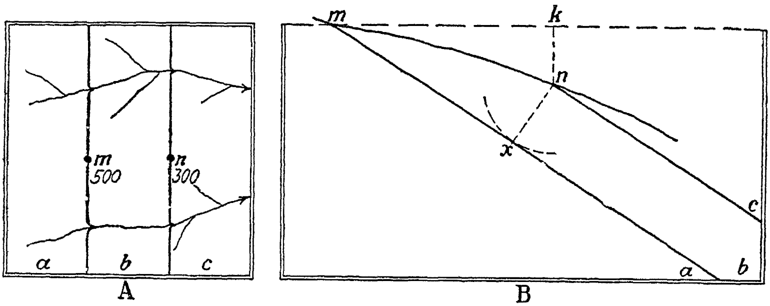


FIG. 25.—Solution for dip, thickness given, beds dipping same direction as topography.

is, of course, not the slope distance mn but the horizontal distance mk. The elevations of m and n are read from the contours. The line nk is the difference in these elevations.

$$mn = \sqrt{mk^2 + kn^2}.$$

$$\tan \angle kmn = \frac{kn}{mk}.$$

$$\sin \angle xmn = \frac{xn}{mn}.$$

$$\text{Dip} = \angle kmn + \angle xmn.$$

There is, however, a much simpler graphic solution of the above problem. In Fig. 25 *B*, draw mk equal to the scaled distance

between m and n on the map. At k drop a $\perp$ kn equal to the difference in elevation between m and n. On n as a center, draw a circle with radius equal to the thickness of the bed nx. From m draw mx tangent to this circle, as shown. Scale the dip angle kmx with the protractor.

Again, in Fig. 26 *A*, the conditions are the same, except that mn slopes to the west, opposite to the dip of the beds. Figure 26 *B* is, again, a cross-section, mn once more representing a topographic surface, this time sloping opposite to the dip of the

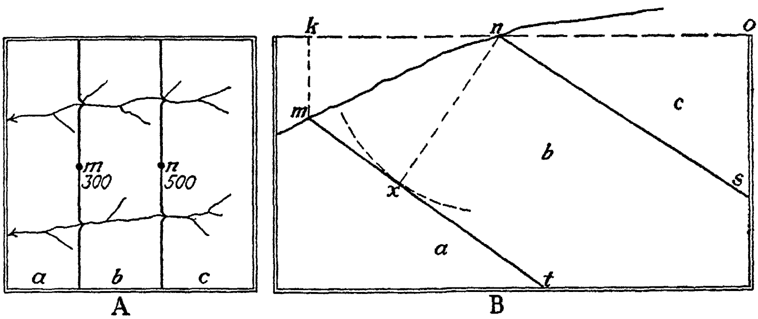


FIG. 26.—Solution for dip, thickness given, bed dipping opposite to topographic slope.

beds, with nk the horizontal distance scaled from the map, and mk the vertical distance determined from the contours between points m and n, chosen at the base and top of formation b, and in a line normal to the strike.

As before,

$$mn = \sqrt{mk^2 + kn^2}.$$

$$\tan \angle knm = \frac{mk}{kn}.$$

$$\cos \angle xnm = \frac{xn}{mn}.$$

$$\text{Dip angle } sno = 180° - (90° + \angle xnm + \angle knm).$$

Graphically, this may be solved much as was the former case. If km and kn are drawn to scale, and a circle with xn radius

(the thickness) be drawn about n, a tangent, mx, to this circle from m (Fig. 26 B) will represent the base of the bed. Through n draw ns parallel to mx and scale the dip angle sno with a protractor.

The chief value of the above solutions lies in the fact that they emphasize the effect of topographic slope on width of outcrop. The student should work on such cases until he understands the principle thoroughly. On the Mercersburg quadrangle (Folio 170) the belt of Juniata formation (Oj) 3 inches from the west

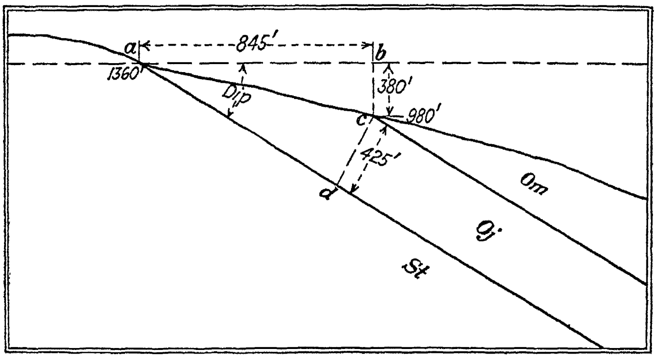


Fig. 27.—Solution for dip, thickness given, bed dipping in direction of topographic slope.

end of the reference line *D-D* affords a good opportunity for the testing of the method. At that point a dip arrow indicates a dip of 45° nearly on the line *D-D*, the beds being overturned. According to the text of the folio, the formation ranges from 400 to 450 feet in thickness. Since it is not possible to determine the thickness at this particular point, it is best to assume an average figure of 425 feet. The beds dip in the same direction as the slope of the topography. A section on *D-D* is represented in Fig. 27. The line *ab* is the distance across the outcrop normal to the strike, taken along the reference line *D-D*, and is about 0.16 mile, or 845 feet. The elevation at the west contact is

about 1,360 feet, at the east contact about 980 feet, or a difference, bc, of 380. The computation follows:

$$\begin{aligned}
ac &= \sqrt{ab^2 + bc^2} && = 927 \text{ feet.} \\
\tan \angle bac &= {}^{380}\!/_{845} && = 0.4497. \\
\angle bac &= 24° \, 13' && \\
\sin \angle cad &= {}^{425}\!/_{927}. && = 0.4585. \\
\angle cad &= 27° \, 18' && \\
\text{Dip} &= 24° \, 13' + 27° \, 18' && = 51° \, 31'.
\end{aligned}$$

The figure given on the map is 45°. Compared with this, the 51° 31′ just determined appears like a large error. The sources of this discrepancy may be looked for (1) in the fact that dips taken in the field are not accurate for more than the exact point at which taken, and may vary by several degrees in the distance across the outcrop. (2) In the fact that the contacts may not be shown at quite the proper elevations. (3) In the fact that the width of belt on the map may be in error by a considerable amount. This is likely to be an important source of error, as on an inch-to-the-mile scale exact representation of small horizontal distances is impracticable. (4) In the difficulty of reading the map closely with crowded contours and small distances. (5) In the fact that the thickness of the formation may be variable from place to place.

If, however, the topography had been neglected entirely, the solution (p. 243) would have been

$$\sin \text{dip} = \frac{425}{845},$$

from which the dip would appear to be 30° 12′, which is much farther from the truth than the figure obtained above.

A computation can also be made (Mercersburg sheet) on the belt of Martinsburg shale (Om) 2 inches east of the west end of the fifty-five minute parallel. Here the beds dip east and the topographic slope is to the west. A section along the parallel is represented in Fig. 28.

The line *ab* is the distance across the formation normal to the strike, on the parallel, and is about 0.63 mile, or 3,326 feet. The lower contact *c* is at an elevation of 1,200 feet, the upper

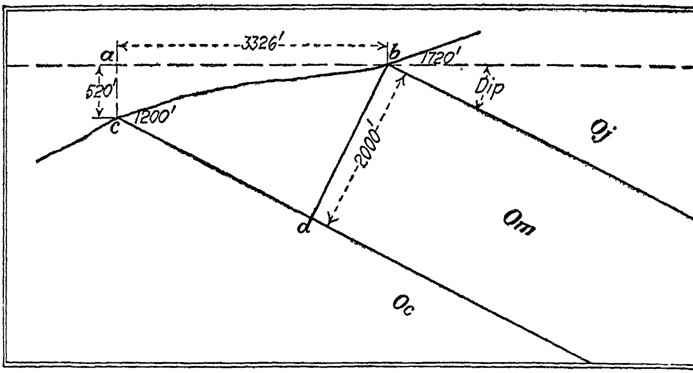


FIG. 28.—Solution for dip, thickness given, beds dipping opposite to topographic slope.

contact *b* at 1,720 feet, making *ac* 520 feet. The thickness of the formation *bd* is given in the text of the folio as 2,000 feet.

$$
\begin{aligned}
bc &= \sqrt{3{,}326^2 + 520^2} = 3{,}366. \\
\tan\angle abc &= 520/3{,}326 = 0.1564. \\
\angle abc &= 8^\circ\ 53' \\
\cos\angle cbd &= 2{,}000/3{,}365 = 0.5942. \\
\angle cbd &= 53^\circ\ 33' \\
\text{Dip} &= 180^\circ - (90^\circ + 53^\circ\ 33' + 8^\circ\ 53'), \\
&= 27^\circ\ 34'.
\end{aligned}
$$

The figure on the map is 28°. The check is closer than the method can usually be expected to give. Had the topography been neglected, the solution would have been:

$$\sin \text{dip} = 2{,}000/3{,}326 = 0.6013,$$

from which the dip would appear to be 36° 58′.

Another favorable place for checking is 2 inches from the west end of reference line *C-C*, on the Tuscarora formation (St). Here the dip is east and the topography slopes east. A section along *C-C* is represented in Fig. 29.

Line *ab* is the distance across the formation, normal to the strike, on *C-C*, and is approximately 0.52 mile, or 2,745 feet. The stratigraphically lower contact *a* is at 2,020 feet, the upper

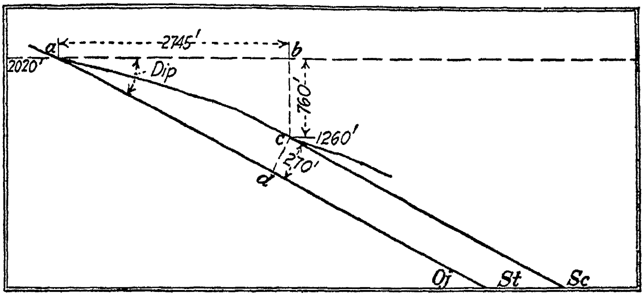


FIG. 29.—Solution for dip, thickness given, bed dipping in direction of topographic slope.

contact *c* at 1,260 feet, making *bc* 760 feet. The thickness of the formation *cd* is given in the text as 270 feet.

$$ac = \sqrt{2{,}745^2 + 760^2} = 2{,}848 \text{ feet}$$

$$\tan \angle bac = {}^{760}/_{2{,}745} = 0.2768.$$

$$\angle bac = 15° \; 28'$$

$$\sin \angle dac = {}^{270}/_{2{,}848} = 0.0948.$$

$$\angle dac = 5° \; 26'$$

$$\text{Dip} = 15° \; 28' + 5° \; 26' = 20° \; 54',$$ whereas the figure on the map is 30°. If the topography had been ignored in this computation, the solution would have been:

$$\sin \text{dip} = {}^{270}/_{2{,}745} = 0.0984,$$

from which the dip would appear to be only 5° 39′.

All of the above problems should also be checked by the student by means of the graphic solutions explained on pages 244–245 and 245–246, inasmuch as the graphic solution demands a sketch to scale, showing the actual structural relations.

While the results in the above type of computation are not entirely satisfactory, the discrepancies result from the inaccuracy of the data used, not from any inherent error in method of procedure (p. 247). The inaccuracy of the data is chiefly owing to the impracticability of close representation and measurement of distances on maps of this scale, and the difficulty in the field of an accurate placing of contacts. In every case worked out, however, the results are more nearly accurate than those obtained if the topography is neglected, and the greater the topographic slope the more necessary it becomes to use some correction such as that employed above.

If the dips are low, but "V's" are lacking from which to make computations, a simple modification of the above method may be employed. It may be used to advantage in an area such as that mapped in the Columbus folio (No. 197). According to the text of this folio, the Ohio shale (Doh) varies between 600 and 650 feet in thickness, and an average of 625 feet may be assumed. The north border of the map is essentially normal to the strike. The elevation of the base of Doh on the west side of Olentangy River (north border of map) is 920 feet. The elevation of the top of the formation, east of Rome (north edge of map), is also 920 feet. If the formation is 625 feet thick,the base at the latter point is approximately 625 feet lower than the top, or 295 feet. If the base on Olentangy River is 920 feet, and the base east of Rome 295 feet, the lower contact dips 625 feet, in a distance of 10 miles measured normal to the strike. The dip is, therefore, about 62½ feet per mile, or about ⅔°.

The sources of error in such a computation are: (1) Inaccuracies of the map, which may be considerable in a region covered, as this is, with glacial drift. (2) Difficulty in reading elevation and distances. On this map, with the 20-foot interval and so little dissection, this error is small. (3) An assumption that the

thickness, 625 feet, is the same as the vertical distance from top to base of the formation. The error introduced by such an assumption is wholly negligible, with dips up to 10°, as shown on pages 219–220. (4) Error in the thickness of the formation, which was determined from well records.

It is hardly conceivable that with the 20-foot interval employed, the total error in reading both contacts could reach 100 feet, even in this drift-covered area, since the irregular nature of the contact at both points of observation indicates some little detail in mapping. If such is the case, the result is within 10 feet per mile of being correct, if the reported thickness of the formation is dependable. Of course, it will be understood that this represents the *average dip* across this one formation at the north border of the map, and even in this restricted area it may be higher in some places and lower in others than the figure given.

Another good place to apply this method is where the reference line *F-F* crosses the outcrop of the Pierre shale (Kp) on the Newcastle folio (No. 107). According to the text, the Pierre is 1,250 feet thick. Its west contact (top) is at 4,000 feet, the east contact (base) at the same elevation. The base of the formation is, therefore, 1,250 feet lower on the west side of the outcrop than on the east, in a distance of 11.7 miles measured normal to the strike. This is equivalent to a dip of about 107 feet per mile, or approximately 1° 10′.

It is obvious that, where *B-B* crosses the same formation, the dips are considerably steeper, as evidenced by the much narrower outcrop. On *B-B* the east (basal) contact of the Pierre is at 4,050 feet. The west contact (top of the formation) is at 4,150 feet, and, if the formation is 1,250 feet thick, the base at the west side would be 1,250 feet lower, or 2,900 feet. The formation, therefore, dips from 4,050 to 2,900 feet, or 1,150 feet in a distance of 4.3 miles, or about 267 feet per mile, equal to nearly 3°.

For additional maps suitable for dip problems consult the lists of maps showing regional dip (pp. 220 and 221), and the lists showing shape of outcrop in dipping beds (pp. 221 and 230).

DETERMINATION OF THICKNESS

Maps

127. Sundance folio, Wyo.-S. D.
141. Bald Mountain-Dayton folio, Wyo.
142. Cloud Peak-Fort McKinney folio, Wyo.
160. Accident-Grantsville folio, Md.-Pa.-W. Va.
170. Mercersburg-Chambersburg folio, Pa.
186. Apishapa folio, Colo.
193. San Francisco folio, Cal.

Methods for determining the thickness of beds that are horizontal, or nearly so, are given on pages 218 to 220. It has been shown (pp. 219–220) that with moderately dipping beds the same methods can be used to determine thickness as with horizontal formations, provided the observations be taken along the strike line.

n order to determine the real value of this method, a number of specific applications are cited. Using the Sundance folio (No. 127), the patch of Morrison and Lakota (Km and Klk) an inch from the west end of reference line *D-D* has a strike about N. 18° E. At the north end of this patch on almost any possible strike line, the difference in elevation between the base and the top of the Morrison is from 2½ to 3 intervals, or 125 to 150 feet. In the text of the folio the thickness is given at from 125 to 150 feet. Had the elevation of the base been taken on the west side, on *D-D* (4,650 feet), and the top on the east side on *D-D* (5,125 feet), the apparent thickness would have been 475 feet, whereas, had the elevation of the top been taken at the west (4,800 feet) and the base on the east (5,025 feet), the resulting figure would be purely negative. This illustrates the absolute necessity, in dipping formations, of taking observations close together and on a strike line. The case just presented is perhaps extreme, in that no one would be likely to choose points so far apart to get thicknesses. A more nearly representative case is to be found at the exact southeast corner of T. 48 N., R. 63 W., where the top of the Lakota (Klk) is at about 5,200 feet. North, nearly on the strike line, its base is at 5,000 feet, a thickness of 200 feet,

whereas to the west its base is at 4,750 feet, an apparent thickness of 450 feet. The figure given in the text of the folio is from 150 to 300 feet.

A very instructive case occurs on the Grantsville quadrangle (Folio 160) where Savage River crosses the belt of the Pottsville (Cpo) formation (S. cent. rect.). If the strike line be carefully drawn between intersections of the 2,000-foot contour with the upper contact of Cpo, the elevations of base and top are about 1,550 and 2,000 feet, giving a figure of 450 feet for the thickness of the Pottsville. This checks the figure given in the text of the folio. Thicknesses taken in any other direction are, obviously, incorrect, because of the modifying effect of dip on the elevations of contacts.

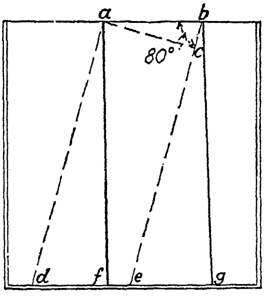


FIG. 30.—Approximate equivalence on a map, of thickness of bed and width of outcrop with steep dips.

Another case worth studying occurs on the Apishapa folio (No. 186), on Mustang Creek (N. cent. rect.). Along the 5,100-foot strike line on the upper surface of the Carlile shae (Kcr), the difference in elevation of the base and top of the formation is about 175 feet. On the crest of the divide, between this and Peterson Canyon, both base and top of the formation are at 5,200 feet, an apparent thickness of zero. The figure given in the text for the Carlile is from 200 to 232 feet.

If the formations are vertical, the width of outcrop is equal to the thickness of the formation, which can be scaled from the map. For all practical purposes, this can be done with beds departing as much as 10° from the vertical, that is, with dips between 80 and 90°, the results still being well within the limits of accuracy imposed by other factors in the problem. In Fig. 30, let *afgb* be a vertical formation, with *ab* the thickness of bed and also the width of outcrop. Let *adeb* be a bed dipping 80°, that is, 10° from the vertical, in which *ac* is the thickness. Assume the width of outcrop *ab* to be 500 feet. In $\triangle$ *abc*, sin

$\angle\, abc = \frac{ac}{ab}$, whence $ac = ab \sin \angle\, abc, = 500 \times 0.98480 = 492$ feet. In other words, with a width of outcrop of 500 feet, the assumption that the beds are vertical only introduces an error of 8 feet, which is far within the allowable limits. Even with a dip of 70°, that is, a variation of 20° from the vertical, the error is only 30 feet for an outcrop 500 feet wide. For a dip of 60°, it would be about 67 feet; for one of 50°, about 117 feet.

In general, on the newer maps, the absence of "V's" means steep, though not necessarily vertical, beds (pp. 224–225); and on such maps any belt of rocks that shows no "V's" where crossed by deep valleys affords a favorable place to use this method, bearing in mind always that other factors make the results only a crude approximation.

The serious error in a measurement of this sort is the inaccuracy of field mapping. Almost invariably a thin formation in vertical or steeply dipping position is much exaggerated on the map. Moreover, any departure from verticality gives a result greater than the actual thickness. Therefore, though this method may usually be depended on to give the maximum limit, the actual result is likely to be reliable only with rather thick formations and on fairly detailed maps of large scale.

On Bald Mountain quadrangle (Folio 141), for instance, in sec. 24, T. 55 N., R. 92 W., the beds dip 80°. The Amsden formation (Ca) has an outcrop about 0.08 mile wide, so the thickness of the formation may be inferred to be less than 0.08 of 5,280 feet, or 422 feet in thickness. According to the text, its maximum thickness is 375 feet. At the same point, the Tensleep sandstone (Ct) occupies so narrow a belt that it is very hard to measure, but in comparison with the Amsden might be estimated as about 0.05 mile, or 264 feet. The text gives its thickness as from 30 to 150 feet. The Sundance (Jsd) occupies a belt of almost the same width (264 feet), the thickness being given in the text as from 250 to 350 feet. The Morrison (Km), which occupies a still narrower belt, is from 100 to 300 feet thick, and the Cloverly (Kcv), which is almost identical in width on

the map, ranges from 30 to 300 feet in thickness. On the other hand, the Chugwater (Trc), which occupies a belt not over 0.15 mile, or 792 feet in width, ranges, according to the text, from 750 to 1,200 feet in thickness. The natural explanation is that the thinner units were exaggerated in mapping at the expense of the thicker formations.

On the Fort McKinney quadrangle (Folio 142) a dip of 85° is shown in sec. 15, T. 50 N., R. 83 W. There the Tensleep sandstone (Ct) has a belt of outcrop about 0.05 mile, or about 264 feet, in width. According to the text, it ranges from 100 to 350 feet in thickness. At the same point, the Sundance (Jsd) occupies a belt about 0.13 mile, or 686 feet, in width. Its thickness is from 300 to 450 feet. The width of the Chugwater (Trc) outcrop is about 0.2 mile, or 1,056 feet. Its thickness is given as 800 to 1,400 feet.

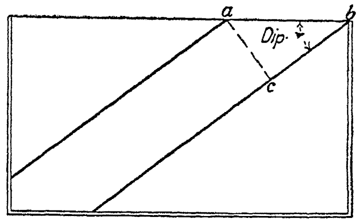


FIG. 31.—Solution for thickness, dip given, topography horizontal.

An excellent illustration of the fact that these very narrow belts are not drawn accurately to scale, the thinner ones being exaggerated at the expense of the thicker, is to be seen in the Haywards quadrangle (Folio 193). The Tice shale (Tt) and the Hambre sandstone (Th) are both mapped (NE. sect.) about the same width, on the average. Since they are contiguous formations, they probably have nearly the same dip. Still, the Tice, which is only 400 feet thick (see text), occupies as wide a belt as the Hambre, which is 1,200 feet thick.

With known dips, and horizontal topography, the thickness of a formation may easily be computed. In Fig. 31, *ab* may be measured from the map, normal to the strike. If angle *abc* is given, or can be measured in any way, then

$$\sin \angle abc = \frac{ac}{ab}, \text{ whence the thickness, } ac = ab \sin \angle abc.$$

If the topography is not horizontal, correction must be made, exactly as in the dip problems on pages 243–251. For example, on the Mercersburg quadrangle (Folio 170), the belt of Martins-

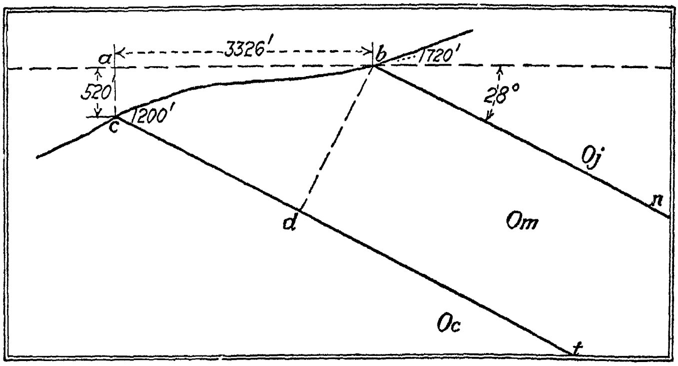


FIG. 32.—Solution for thickness, dip given, beds dipping opposite to topographic slope.

burg shale nearest the west end of the fifty-five minute parallel dips 28° in the opposite direction to the topographic slope. Figure 32 represents a section on the parallel.

ab = the distance across the formation, normal to the strike = 0.63 mile, or about 3,326 feet.
c = the west or basal contact, at a 1,200-foot elevation.
b = the east or top contact, at a 1,720-foot elevation.

$$ac = 1{,}720 \text{ feet} - 1{,}200 \text{ feet} = 520 \text{ feet.}$$
$$bc = \sqrt{520^2 + 3{,}326^2} = 3{,}366 \text{ feet.}$$
$$\tan \angle abc = \frac{520}{3{,}326} = 0.1564.$$
$$\angle abc = 8^\circ\, 53'.$$
$$\angle cbd = 180 - (90^\circ + 28^\circ + 8^\circ\, 53') = 53^\circ\, 7'.$$
$$\cos \angle cbd = \frac{bd}{bc}.$$
$$\text{Whence } bd = 3{,}366 \times 0.6002 = 2{,}020 \text{ feet.}$$

This checks with the thickness given in the text (2,000 feet) more closely than may usually be expected of such determina-

tions. As in the preceding type, the chief sources of error here are: (1) the inaccuracies of placing the contacts on the map, which increase with thinner beds; (2) the errors of reading the map, which decrease with larger scale and smaller contour interval; and (3) the assumption that the dip is constant across the formation. Compare this solution with the one for dip on page 248.

From Fig. 32 this problem may be solved graphically. Draw *ab* a horizontal line to scale, representing the distance in feet

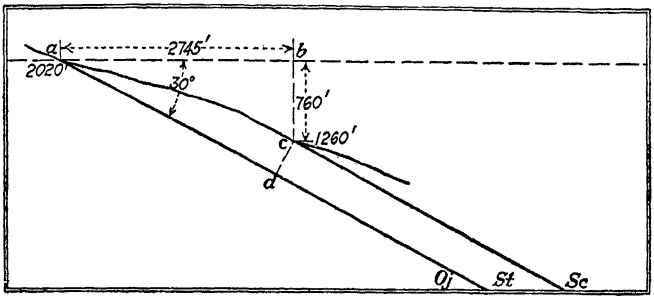


FIG. 33.—Solution for thickness, dip given, beds dipping in direction of topographic slope.

across the formation normal to the strike. Draw *ac* a vertical line equal to the difference in elevation of the two contacts. Then *bc* represents the topographic slope across the formation. From *b* draw *bn* making an angle of 28° with the prolongation of *ab*. Through *c* draw a line *cx* parallel to *bn*. From *b* drop *bd* normal to *cx*. Scale *bd*, which is the desired thickness.

Had the topography been ignored in this problem, the computation would have been

$$\sin 28° = \frac{\text{thickness}}{3{,}326},$$

from which the thickness would have appeared to be 1,562 feet

Another favorable place for the application of this method is the westernmost point where *C-C* crosses the Tuscarora (St). A section on the reference line is represented in Fig. 33.

ab = the distance across the formation, normal to its strike, about 0.52 mile, or 2,745 feet.

a = the west (basal) contact, at a 2,020-foot elevation.

c = the east (top) contact, at a 1,260-foot elevation.

$$bc = 2{,}020 \text{ feet} - 1{,}260 \text{ feet} \qquad = 760 \text{ feet.}$$

$$ac = \sqrt{760^2 + 2{,}745^2} \qquad = 2{,}848 \text{ feet.}$$

$$\tan \angle bac = \frac{760}{2{,}745} \qquad = 0.2768.$$

$$\angle bac = 15° \, 28'.$$

$$\angle cad = 30° - 15° \, 28' \qquad = 14° \, 32'.$$

$$\sin 14° \, 32' = \frac{dc}{2{,}848}.$$

$$\text{Whence } dc = 2{,}848 \times 0.2509 \qquad = 715 \text{ feet.}$$

According to the text, the Tuscarora is only 270 feet thick. The sources of error are the same as in the preceding solution, from which it differs only in the relation of direction of dip of beds to slope of topography. This should be compared with the solution for dip on page 249. A graphic solution for this would be essentially the same as that for the preceding case.

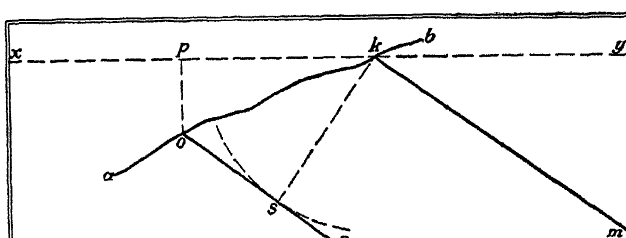


FIG. 34.—Method of determining width of outcrop, thickness and dip of bed being known.

From the discussions on pages 250–251, it should be perfectly clear that solutions depending on the measured width of outcrop, especially of narrow belts of formation, are only crude approximations to the truth, the degree of accuracy increasing with the scale of the map and with the width of the belts. Sudden unrecorded changes in dip and thickness also complicate the

problem. However, solution of such problems is profitable, inasmuch as it emphasizes the relation of outcrop to topography more definitely than can be done in any other way.

If a topographic base is available, a modification of these problems can be and often is utilized in the making of geologic maps. For instance, in Fig. 34, *ab* is the topographic slope across a dipping formation, plotted carefully to scale. The top contact of a formation is located at *k*, the beds dipping opposite to the topography at an angle of 40°. Through *k* draw a horizontal *xy*. At *k* construct the dip angle *mky* as 40°. The position of the lower contact being covered under talus can be located approximately, if the average thickness of the formation is known. If this is 500 feet, draw a circle of 500-foot radius about *k* as a center, and draw a tangent *sn* to this circle, parallel to *km*. Prolong it to interesect the topographic slope at *o*. From *o* draw a normal to *xk* at *p*. Then *pk* is the width of outcrop of the formation.

Most of the maps used as illustrative and supplementary under the discussion of "Determination of Dip" (pp. 236 and 251) are also suitable for use in additional drill on determination of thickness.

FOLDS

ANTICLINES VERSUS SYNCLINES

Maps

61. Monterey folio, Va.-W. Va
78. Rome folio, Ga.-Ala.
85. Oelrichs folio, S. D.-Neb.
93. Elkland-Tioga folio, Pa.
107. Newcastle folio, Wyo.-S. D.
108. Edgemont folio, S. D.-Neb.
127. Sundance folio, Wyo.-S. D.
128. Aladdin folio, Wyo.-S. D.-Mont.
145. Lancaster-Mineral Point folio, Wis.-Iowa-Ill.
150. Devils Tower folio, Wyo.
160. Accident-Grantsville folio, Md.-Pa.-W. Va.

164. Belle Fourche folio, S. D.
170. Mercersburg-Chambersburg folio, Pa.
174. Johnstown folio, Pa.
175. Birmingham folio, Ala.
179. Pawpaw-Hancock folio, Md.-W. Va.-Pa.
214. Raton-Brilliant-Koehler folio, N. M.-Colo.

An anticline is an upwarp of strata that were laid down in essentially horizontal position. Since in undisturbed strata the oldest bed is at the base, and since in the center of an anticline beds are higher than the same beds in adjacent areas, it follows that erosion will cause older rocks to be exposed in the center of the arch than are exposed elsewhere (Figs. 13 *A* and 35 *A*).

In a syncline, on the other hand, the beds are downwarped, and erosion will cause the youngest formation to be exposed at the center, surrounded successively by older rocks (Figs. 13 *B* and 35 *B*).

Although on a few maps dips are indicated by symbols ($\angle 3^\circ$) and the folds can, therefore, be recognized as anticlines or synclines, depending on whether the formations dip away from the axis or towards it, one is often compelled to use the age of beds in recognizing the type of fold.

In general, the "V's" formed where streams cross folds also give indication of the structure. In a normal anticline dips are outward from the axis and the "V's" point outward on opposite sides of the fold; in a normal syncline the beds dip toward the center and the "V's" point inward.

The strike of a fold is the trace of its axial plane (Fig. 35) on the horizontal. An approximation to the strike may be found by bisecting the angle made on the map by the general strike of each flank, though in an asymmetrical fold the trace of the axial plane lies somewhat nearer the outcrop of the steeper flank.

On the Grantsville quadrangle (Folio 160) the long, narrow belt of Jennings formation (Dj) occupies the crest of an anticline, with younger beds on either side. The strike of the fold is about N. 40° E. On the southeast flank, with its southeast dips, the numerous "V's" point southeast. On the northwest flank,

with opposite dips, the "V's" point in the opposite direction. The much broader belt of Conemaugh (Ccm) in the west central and north central rectangles occupies the trough of a syncline striking about N. 32° E., with older formations on either side, the "V's" pointing inward toward the axis from the flanks.

The question of whether the axis of a fold is a valley or a ridge is not a function of the type of fold, but of the character of the rock exposed at the center, and of the stage of erosion. On the Monterey folio (No. 61), Wilson Run (E. cent. rect.) occupies the crest of an anticline striking N. 30° E. South Branch (NE. rect.) also follows the crest of an anticline, while the long narrow strip of Devonian between occupies a syncline. Michael Mountain (W. cent. rect.) is an anticline, the central outcrop of which is the Tuscarora quartzite (Stc), a very hard ridge maker. On the other hand, Wilson Run is an anticlinal valley carved out on the much less resistant Shenandoah limestone (€Ss) with ridges of the younger Tuscarora on either side. With further erosion, the Tuscarora will be cut through on Michael Mountain, finally exposing the Shenandoah at the center. At this stage, there will be two mountains with an anticlinal valley between.

The synclinal patch of Romney shale (Dr) in the northeast rectangle is traversed by a longitudinal valley not because it is a syncline, but because the Romney is less resistant than some of the adjacent formations. If the central outcrop of a syncline were of greater resistance than the bordering formations, the syncline would constitute an upland area. This is the case with the broad strip of Oswayo formation (CDo) across the Elkland and Tioga quadrangles (Folio 93).

Of course, even in flat-lying rocks, the uplands are capped with younger formations, entirely surrounded by older beds. Round Mesa (Raton quadrangle, Folio 214), though capped with rock younger than that surrounding it, gives no evidence of being synclinal. The strip of Oswayo (CDo) across the Tioga quadrangle, on the other hand, gives evidence on each flank of dips inward toward the axis. Using the principles laid down on

pages 240–242, these dips can actually be determined with considerable accuracy.

The small patches of Oswayo (CDo) in the northwest portion of the Elkland quadrangle (Folio 93) occupy the trough of another syncline, the approximate strike of which is found, by connecting up the various patches, to be about N. 70° E.

The presence of an anticlinal axis may sometimes be revealed by a number of inliers, where streams cross the fold, even in regions where the rocks are very nearly horizontal. Two such axes are plainly visible on the Lancaster-Mineral Point folio (No. 145). One exposes inliers of the St. Peter (Osp) and Prairie du Chien (Op) on all the larger streams from Mineral Point west to Lancaster, the other from Red Rock west to Potosi. Such inliers must not be confused with those produced on regularly dipping beds by change in stream gradient from steep at the source to gentle in the lower reaches. The inliers on the Lancaster and Mineral Point sheets occur on that portion of many of the streams where the gradient is regular, and so must result from changing dip. Compare these cases carefully with those described on pages 227–228. Both anticlines described above are very low arches, striking nearly east and west. Since the valleys have more nearly north-south lines, the inliers are elongated almost at right angles to the axes of the folds, whereas in more intense folding, such as that on the Monterey folio (No. 61), the inliers are chiefly elongated parallel to the axes.

A very fine example of an inlier elongated at right angles to the general strike of the fold is to be seen on the Johnstown folio (No. 174), where Conemaugh River crosses the Laurel Ridge anticline. The axis of the fold strikes about N. 40° E., whereas the inlier of Catskill (Dck) is elongated parallel to the transverse river, that is, about N. 20° W.

Folds sometimes split, as on the Birmingham folio (No. 175), on which the prominent anticline passing through Birmingham divides into two branches (in the E. cent. rect.), the intervening syncline being occupied by a large area of the Pottsville formation.

It not uncommonly happens that an anticline is so large that only one flank of it shows on a single map. An especially fine example is the Black Hills. The Oelrichs folio (No. 85) shows the southeast dips off the dome; the Edgemont (No. 108), New-castle (No. 107), and Sundance (No. 127), the southwest dips; Devils Tower (No. 150), the northwest flank; and Aladdin (No. 128) and Belle Fourche (No. 164), northeast dips.

Minor folds not uncommonly occur on the flanks of larger structures. The anticline of Conococheague limestone (Ꞓc) at the center of the south border of the Mercersburg quadrangle (Folio 170), for instance, shows on its east flank a minor anticline separated from the major fold by a syncline of Beekmantown limestone (Ob). The anticline has older Ꞓc in the center, surrounded by younger Ob; the syncline is just the reverse. On the Hancock quadrangle (Folio 179), the small point of Romney shale (Dr) just northwest of the intersection of the reference line *F-F* with the five minute meridian is a minor anticline, and the corresponding point of Jennings formation (Dj) a minor syncline, on the flank between the major syncline to the west and the major anticline to the east. That these are not "V's" related to valleys is shown conclusively by their complete disregard for the topography.

When folds have a sufficient number of these minor folds to be termed synclinoria or anticlinoria, their most obvious characteristic is the nature of the outcrop at the pitching end (see also pp. 267–270). A particularly striking example is the end of the anticlinorium shown by the Parkhead sandstone (Dph) in the vicinity of Highland Church, in the southwest rectangle of the Hancock quadrangle (Folio 179). At this point the structure is somewhat obscured to a beginner by the fact that the Parkhead is a member, with Jennings outcropping both within and without the anticline. Its relation to the adjacent syncline on the east, however, is distinctive.

The trough of Carboniferous in the south central and central rectangles of the same map is also not a simple syncline, but rather a synclinorium, as will be seen by noting the minor folds

displayed at its north end, in the trace of the Parkhead sandstone (see also p. 270).

An exception to the general principle that the youngest beds occur in the center of a syncline and the oldest in the center of an anticline occurs when older beds are overthrust onto younger, and then folded. Of course, the highest beds, in such a case the oldest, are folded into the center of the syncline, whereas erosion of a corresponding anticline exposes the underlying but younger beds at the center. The Rome folio (No. 78) affords a remarkable example, the nearly round patch (NE. rect.) of Conasauga limestone (Ꞓc) being an older overthrust bed, a remnant of which remains in a syncline. The area just east of it is an anticline exposing the younger bed at its center.

Additional maps showing anticlines and synclines

8. Sewanee folio, Tenn.
20. Cleveland folio, Tenn.
21. Pikeville folio, Tenn.
27. Morristown folio, Tenn.
36. Pueblo folio, Colo.
59. Bristol folio, Va.-Tenn.
79. Atoka folio, Okla.
123. Elders Ridge folio, Pa.
141. Bald Mountain-Dayton folio, Wyo.
173. Laramie-Sherman folio, Wyo.
186. Apishapa folio, Colo.
196. Philipsburg folio, Mont.
215. Hot Springs folio, Ark.

SYMMETRY AND ASYMMETRY IN FOLDS

Maps

20. Cleveland folio, Tenn.
141. Bald Mountain-Dayton folio, Wyo.

It has already been pointed out that, other factors being constant, the steeper the dip the narrower the outcrop. If, then, with horizontal or nearly horizontal topography, on one flank of a fold a bed has an outcrop much wider than on the other, the limb with the wider outcrop has the gentler dip; in other words, the fold is asymmetrical. This statement applies equally to synclines and anticlines. Also on the steeper flank the "V's" will be shorter than on the more gentle limb.

This is nowhere better shown than in the anticline along Dry Fork Ridge in the northeast rectangle of the Bald Mountain quadrangle (Folio 141). The dips on the southwest flank range from 20 to 85°, those on the northeast flank from 10 to 12°. Corresponding to this, there is a striking difference in width of the outcrop of Madison limestone (Cm), which is from two to five times as wide on the gentle flank as on the steep one. The outcrop of Bighorn limestone (Ob) shows less difference, largely because it is so thin that its belt of outcrop is considerably exaggerated (p. 254). That the delineation of this belt is much generalized might also be suspected from the fact that on the southwest flank it maintains practically the same width from the point of 20° to that of 85° dips.

The asymmetry of this fold is also strikingly shown by the "V's". Those on the northeast flank are long; the few on the southwest flank, in the contact between the Madison (Cm) and Amsden (Ca), for instance, are very much shorter, and where Bighorn River crosses the steep flank no "V" is formed whatever.

The long syncline across the central and northeast rectangles of the Cleveland folio (No. 20) is distinctly asymmetrical, the southeast flank being much the steeper, as shown by its narrower outcrop of the Tellico sandstone (St). The map is one of the older folios, and on a small scale, consequently the "V's" are probably not adequately represented. With more careful mapping, they would doubtless show on the northwest flank, though they might not on the southeast.

Other maps showing asymmetrical folds

36. Pueblo folio, Colo. (N. end fifty minute meridian).
59. Bristol folio, Va.-Tenn. (Brumley Creek, NE. rect.).
61. Monterey folio, Va.-W. Va. (Little Mare Mountain, S. cent. rect.).
78. Rome folio, Ga.-Ala. (Little Sand Mountain, N. cent. rect.).
79. Atoka folio, Okla. (at Lehigh, N. cent. rect.).
175. Birmingham folio, Ala. (Bangor, N. cent. rect.).
215. Hot Springs folio, Ark. (Glazypeau Mountain, N. cent. rect.).

OVERTURNED FOLDS

Maps

12. Estilville folio, Ky.-Va.-Tenn.
59. Bristol folio, Va.-Tenn.
170. Mercersburg-Chambersburg folio, Pa.
179. Pawpaw Hancock folio, Md.-W. Va.-Pa.
196. Philipsburg folio, Mont.

A fold is described as overturned if either limb has passed the vertical, so that both flanks dip in the same direction. The beds are actually upside down in only one limb of such a fold. If dip arrows are given on the map, it is an easy matter to recognize overturned beds, since the younger are clearly dipping beneath the older. On the Mercersburg quadrangle (Folio 170) the beds in Cove Mountain (SW. and W. cent. rects.) are plainly overturned. The Cayuga (Scy) dips southest under the older Clinton (Sc), it, in turn, under the still older Tuscarora (St), that under the Juniata (Oj) which is still older, and the Juniata under the Martinsburg, the oldest formation in the overturned portion of the section.

No streams cut valleys through this overturned portion of the section, so that the relation of the "V's" cannot be seen. It should be obvious, however, that they will, where present, show the direction of dip as well as dip arrows. Along Short Mountain, for instance, on the Hancock quadrangle (Folio 179), there is a pronounced "V" where Cherry Creek crosses the Rockwell formation (SE. cent. rect.), showing that the formation dips east under the older Catskill (Dck). South along the same belt are other less pronounced "V's", all in conformity with the dips indicated by arrows on the map. The area between Sleepy Creek Mountain, and the Third Mountain—Short Mountain range is a syncline, the east flank of which is overturned.

On the Bristol folio (No. 59), there occur along the contact between the Lee and Norton formations in the north central rectangle, several small "V's" pointing downstream to the southeast, indicating that the younger Norton dips southeast

under the older Lee in overturned relations. There are no dip arrows by which to verify this interpretation, but an inspection of the structure sheet of the folio shows this to be a correct inference.

If dip arrows are not given, as they are not on many of the older maps, the only evidence of overturned beds is information as to direction of dip yielded by "V's". Since overturned beds, however, are often dipping at very high angles, many examples completely escape detection on maps. This is the case with the syncline of Newman limestone (Cn) across the south third of the Estilville quadrangle (Folio 12). Though the cross-section sheet shows the south flank of this syncline to be overturned, the lack of dip arrows and "V's" makes it impossible to see this on the areal sheet.

On very recent maps overturned beds are sometimes indicated by the symbol $\nwarrow\!\!\searrow$45°. For illustration, see the outcrop of the Kootenai formation (Kk) in the extreme northeast corner of the Philipsburg folio (No. 196) and the left-hand legend of the same map.

Additional examples of overturned beds

175. Birmingham folio, Ala. (T. 13 S., R. 1 E.).
193. San Francisco folio, Cal. (syncline of Orindo formation, E. cent. rect., Concord quad.).
215. Hot Springs folio, Ark. (Glazypeau Mountain, NW. rect.).
Bull. 691, U. S. Geol. Survey, Pl. XXIV (west border of map).
Bull. 713, U. S. Geol. Survey, Pl. III (Jura-trias in N. E. part).

PITCH OF FOLDS

Maps

20. Cleveland folio, Tenn.
78. Rome folio, Ga.-Ala.
93. Elkland-Tioga folio, Pa.
160. Accident-Grantsville folio, Md.-Pa.-W. Va.
170. Mercersburg-Chambersburg folio, Pa.
179. Pawpaw-Hancock folio, Md.-W. Va.-Pa.
215. Hot Springs folio, Ark.

If the axis of a fold is not horizontal, the fold is said to have pitch. In Fig. 35 *A* the anticline is pitching slightly east of north; in Fig. 35 *B* the syncline is pitching slightly west of south. It will at once be obvious that the end of an anticline points in the direction of pitch, that of a syncline in the opposite direction. In a pitching fold, the outcrops of a given bed on the two flanks are not parallel, conversely if the outcrops are parallel the visible portion of the fold has no pitch. The angle of inclination of trough or crest from the horizontal is the angle of pitch and

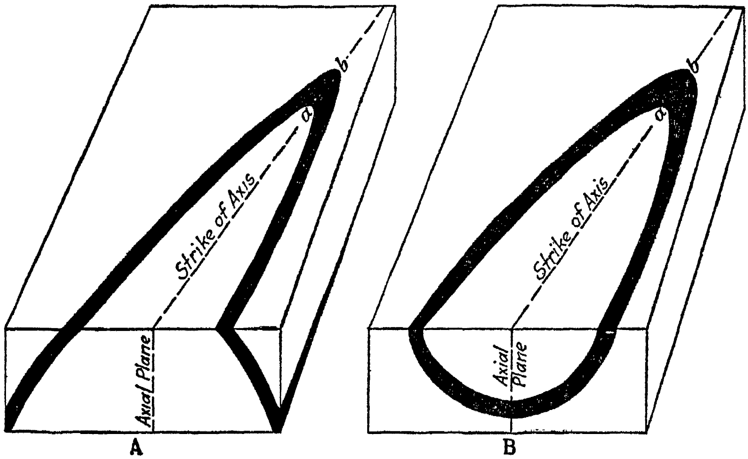


FIG. 35.—Pitching folds, axial plane, and strike of axis.

may be considered as a special case of dip, in the direction of strike of the fold as a whole. On the average, the pitch of a fold is less than the dip on its flanks, in which case the width of outcrop of any given formation will be greater at the end of the fold, in the direction of the axis, than across the fold at other points.

An anticline which shows little or no pitch exposes a belt of Jennings formation (Dj) across the Grantsville quadrangle (Folio 160), and a syncline with essentially horizontal axis across the Tioga quadrangle (Folio 93) is occupied by the Oswayc (CDo) formation.

An anticline pitching slightly west of south occurs at Dickeys Mountain in the northeast rectangle of the Hancock quadrangle (Folio 179), and a syncline pitching in the same direction lies between Sleepy Creek Mountain and Third Hill Mountain (S. cent. rect.).

Folds may pitch at both ends. In the east central part of the Accident quadrangle (Folio 160) is an anticline exposing the Jennings (Dj) and Catskill (Dck) formations, the northest end of which pitches northeast, and the southwest end southwest. In other words, this anticline has been cross-folded anticlinally. The proportions are almost those of a dome.

The syncline of Sevier shale (Ssv) on the Cleveland sheet (Folio 20) pitches southwest on the northeast end, and northeast on the southwest end, that is, it has been cross-folded synclinally. Taylor and Gaylor ridges, in the northwest corner of the Rome folio (No. 78), constitute the northwest flank of a syncline, the northeast end of which pitches northeast and the southwest end southwest, the syncline being cross-folded anticlinally at Holland.

Most of these cases also illustrate the principle that the pitch is usually less than the dip, with consequent wider outcrop on the end than on the flank.

Two synclines and an anticline pitching in the same direction (northeast) are shown in the north central part of the Mercersburg quadrangle (Folio 170), and a whole series of parallel folds pitching southwest in the Hot Springs folio (No. 215).

Minor, or drag, folds on the flanks of larger structures, in general, have the same direction of pitch as the larger unit. This is illustrated in the south central rectangle of the Mercersburg quadrangle (Folio 170), the anticline of Conococheague limestone (Ꞓc), which pitches slightly east of north showing a minor anticline (p. 263) on its east flank, also pitching in the same direction. Similarly, the syncline of Carboniferous in the south central rectangle of the Hancock quadrangle (Folio 179) shows on its east flank a minor syncline of Jennings formation (Dj) extending into the Romney shale (Dr) near the intersection of reference

line *F-F* and the five minute meridian. Both the major syncline and its minor drag fold pitch southwest.

On the Hancock quadrangle, the anticlinorium of Parkhead sandstone (Dph) and Jennings formation (Dj) pitches southwest at its southwest end (SW. rect.), and northeast at the opposite end (p. 263). Each minor fold of the larger structure is represented by a separate point, as in Fig. 36. The crenulation at the initial "H" of "Highland Church", for example, is a

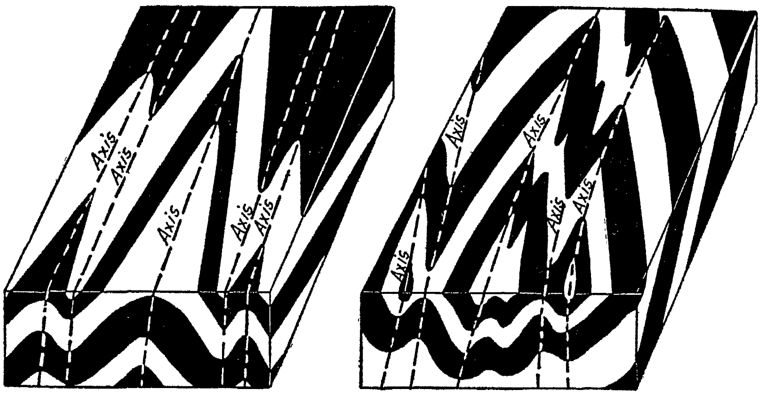


FIG. 36.—Pitching anticlinorium (left) and synclinorium (right).

syncline, pitching southwest; the crenulations on either side of it, pointing in the opposite direction, are anticlines also pitching southwest.

Theoretically, the amount of pitch can be determined at the end of any given outcrop, if the thickness of the formation is known, by using the methods employed for dip, on pages 234 to 250. The width of outcrop is measured as shown on Fig. 35, the desired distance being *ab*, and the elevations being read from the contours at *a* and *b*. The method is subject to the same errors described on pages 247 and 250, with the added danger that the actual width of outcrop in the field is probably less accurately measured along the end than on the side of the fold.

Additional maps showing pitching folds

24. Three Forks folio, Mont.
27. Morristown folio, Tenn.
28. Piedmont folio, Md.-W. Va.
36. Pueblo folio, Colo.
50. Holyoke folio, Mass.-Conn.
61. Monterey folio, Va.-W. Va.
79. Atoka folio, Okla.
92. Gaines folio, Pa.-N. Y.
123. Elders Ridge folio, Pa.
175. Birmingham folio, Ala.
196. Philipsburg folio, Mont.

EFFECT OF EROSION ON WIDTH OF OUTCROP OF FOLDS

From an inspection of Fig. 13 *A*, it will be obvious that, with continued erosion, the lateral outcrops of an anticline will be shifted farther and farther apart, the central outcrop will become wider, and will finally split in two, exposing a still older formation. As the process continues, this central outcrop will widen, split, and expose a yet older bed. With a syncline, on the contrary (Fig. 13 *B*), the lateral outcrops are shifted closer together, while the central outcrop becomes narrower, and finally disappears; the two adjacent lateral belts now merging to form a new central outcrop, which, in turn, will go through the same history.

DATE OF FOLDING

Maps

24. Three Forks folio, Mont.
79. Atoka folio, Okla.

The dating of diastrophism involves a knowledge of the ages of the rock formations. On the map, this is learned from the legend, and although in the field it involves paleontology and comparative stratigraphy, these have no part in the interpretation of maps as such. Although the matter of dating events in geologic time will come up again and again, particularly in connection with faults (pp. 298–299), igneous rocks (pp. 308–312,

unconformity (pp. 319–322) and geologic history (pp. 337–341) it may be stated briefly here that folding ocurred after the deposition of the youngest rocks actually folded, and before the deposition of overlying undisturbed strata.

On the Three Forks folio (No. 24) the folding came after the deposition of the Laramie (Kl) and before the laying down of the Bozeman lake beds (Nb). Some of it appears to have occurred before the deposition of the Livingstone (S. cent. portion of map), and some of it possibly later (NW. corner). On the Atoka quadrangle (Folio 79) the folding obviously occurred after the deposition of the Boggy shale (Cb), the youngest bed to take part in the deformation, and before the Trinity, which is undisturbed.

Additional maps illustrating date of folding

50. Holyoke folio, Mass.-Conn. (after Silurian, and before Jura-Triassic).
56. Little Belt Mountains folio, Mont. (after Laramie—probably after Livingston—and before Smith River lake beds).
78. Rome folio, Ga.-Ala. (after Pennsylvanian and before Lafayette).
98. Tishomingo folio, Okla. (after Carboniferous and before Trinity).
142. Cloud Peak-Fort McKinney folio, Wyo. (between late Cretaceous and Tertiary [?]).

FAULTS

Faults are commonly shown, on maps, with heavy black lines, solid where the fault is proved, dashed where it is uncertain, and dotted where it is concealed beneath younger formations. The lines are heavier than the black contact lines between formations. For illustration, see the legend of the Deming folio (No. 207).

UPTHROWN AND DOWNTHROWN SIDE

Maps

33. Briceville folio, Tenn.
203. Colorado Springs folio, Colo.
215. Hot Springs folio, Ark.

After a faulted area has been eroded to a plane surface, or nearly so, it is obvious that more thickness has been removed

from the upthrown than from the downthrown side, so that, if the beds are not overturned, older formations are exposed on the raised than on the dropped block. This is the common way by which the direction of throw may be distinguished on a map.

On the Colorado Springs folio (No. 203), for example, the main fault exposes pre-Cambrian on the west side, and on the east beds ranging in age from Cambrian to Cretaceous, the east side having dropped with respect to the west. On the Hot Springs folio (No. 215), the fault at Dripping Springs (NW. cor. sec. 30, T. 2 S., R. 18 W.) has younger beds on the west or dropped

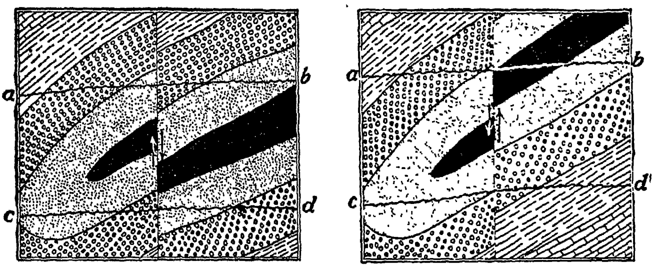


FIG. 37.—Faulting of overturned beds, showing how erosion may produce the normal (*cd*) or abnormal (*ab*) relation of older and younger beds.

side than on the east. Along the main fault across the Briceville folio (No. 33) older beds occur on the east side, which is thereby known to be upthrown.

The normal relations described above may conceivably be reversed when overturned or overthrust beds are cut by younger faults. In such cases older beds rest on younger, so that the younger on the upthrown side can be brought against older on the downthrown. Whether the normal or the abnormal relation will result depends on the relation between the amount of throw and the position of the erosion surface (Fig. 37). The possible variations are many, and the relations complex, though ordinarily there will be other clues as to the reversed position of the beds. No good maps illustrating these rare cases are known.

If the same formation outcrops on both sides of a fault throughout its extent, it is not usually possible, from a map alone, to tell the direction of movement, since there is usually no way to compare the relative ages of the various horizons of a single formation.

Other maps suitable for use in working out upthrown and downthrown sides of faults

111. Globe folio, Ariz.
170. Mercersburg-Chambersburg folio, Pa.
175. Birmingham folio, Ala.
196. Philipsburg folio, Mont.
202. Eureka Springs-Harrison folio, Ark.-Mo.
207. Deming folio, N. M.

AMOUNT OF MOVEMENT

Maps

46. Richmond folio, Tenn.
78. Rome folio, Ga.-Ala.
111. Globe folio, Ariz.
122. Tahlequah folio, Okla.
151. Roan Mountain folio, Tenn.-N. C.

Fault movement may be in any direction. The vertical component of that movement, known as the throw, may be measured on a map within certain limits, where the rocks are horizontal, if the thicknesses of the formations involved are known. For instance, on the Globe special map (Folio 111), the fault at the south end of the forty-six minute meridian brings the Apache (€a) and Globe (DCg) formations into juxtaposition. According to the text, the former has a maximum thickness of 1,000, the latter of 700 feet. From Fig. 38, it will be easily seen that any throw from a few feet (*A*) up to almost the total combined thickness (*B*) of the two formations (1,700 feet) would give this result, if eroded to the proper level. With perfectly horizontal topography either extreme might be approached very closely. The more rugged the dissection the more of each forma-

tion must be present, so that no other beds are exposed; consequently, the nearer the mean the actual throw must be. In this particular case, for instance, over 100 feet more of the Globe formation is still preserved in some places than in others on the downthrown side, all of which abuts against the Apache formation, so the throw cannot be less than 100 feet.

There is also over 100 feet of Apache exposed on the upthrown side, all of which abuts against the Globe, so that it is certain

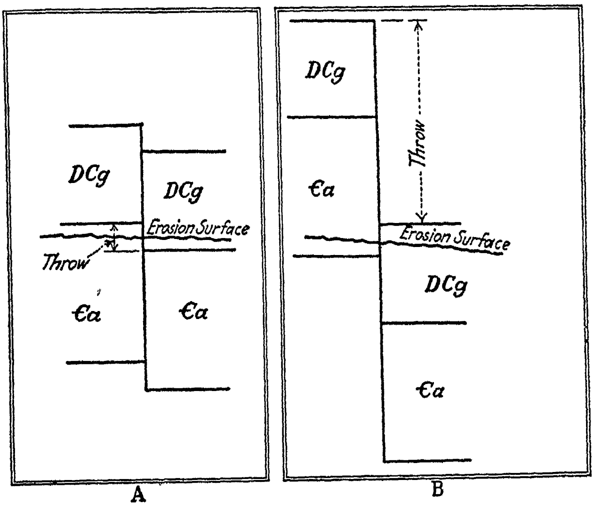


Fig. 38.—Maximum and minimum limit of throw.

the throw cannot be within 100 feet of the greatest possible movement that would still allow the two formations to touch each other, that is, the throw cannot be over 1,600 feet, rather than the 1,700 feet first suggested.

A similar diagram (Fig. 39) shows that if one formation *b* is completely cut out, so that *a* is in juxtaposition with *c* then the least possible throw is limited by the minimum thickness of the formation cut out, whereas the greatest possible throw is nearly the sum total of the thicknesses of the three formations.

With two formations completely cut out, the minimum limit is the sum of the two that are cut out, and the maximum limit their thickness plus that of the next overlying and underlying formations, which have been brought into juxtaposition. With these explanations in mind, it may be stated in more general terms that the throw cannot be less in horizontal beds than the thickness of all formations completely cut out, nor more than this

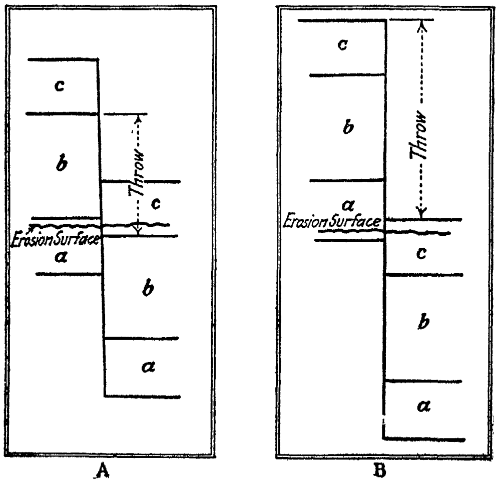


FIG. 39.—Maximum and minimum limit of throw.

thickness plus that of the two formations brought into juxtaposition.

This, of course, can be made somewhat more definite by considering the degree of dissection, as in the first case explained.

Good examples are to be found on the Tahlequah folio (No. 122). On the west line of sec. 3, T. 15 N., R. 22 E., a fault drops the Winslow (Cwl) formation to the level of the Boone (Cbn). The least possible throw is the minimum thickness of the beds cut out, the Fayetteville (Cfv = 20 feet), Pitkin (Cp = 3 feet), and Morrow (Cmr = 80 feet), or, in all, 103 feet. The greatest possible throw cannot be more than the maximum thickness for

each of these, plus that of the Boone and the Winslow. These are Cbn = 375 feet, Cfv = 160 feet, Cp = 80 feet, Cmr = 210 feet, and Cwl = 900 feet, or a total of 1,725 feet. These figures would apply, as limits to our interpretation, if there were no dissection. In this vicinity, however, the dissection is such that the base of the Winslow (exposed) is at least 150 feet below the top of the Boone, part of which is eroded, so the throw must be at least 150 feet more than the minimum figure of 103 feet given above, or certainly not less than 253 feet. On the other hand, the base of the Winslow is at least 100 feet above the base of the Boone (the latter not yet exposed), so that the base of the Winslow can have dropped no more than past the maximum thicknesses of the three formations cut out plus 275 feet of the total 375 feet of Boone. This would be Cbn = 275 feet, Cfv = 160 feet, Cp = 80 feet, Cmr = 210 feet, or a total not to exceed 725 feet.

If the same contact is exposed immediately adjacent to the fault, on both sides of the break, the throw can be determined as closely as contours can be read, the difference in elevation of the given contact on the two sides being the amount of vertical movement, provided, of course, the beds are horizontal, or essentially so. At the point on the Richmond quadrangle (Folio 46), for instance, where the reference line *A-A* crosses the southernmost of the two faults in the northeast rectangle, the base of the Richmond formation on the north or upthrown side is at about 1,000 feet in elevation, whereas on the south or dropped side it is at about 700 feet, a throw of approximately 300 feet.

In the above method, the chief sources of error are: (1) the inaccuracy of drawing contacts in the field; (2) the difficulty of reading contours closely, especially on small-scale and large-interval maps; and (3) the probability that the beds are not perfectly horizontal.

If the same contact cannot be seen on both sides of the fault, but at least one is visible on each side, the throw can be determined rather closely, provided the thicknesses of the beds

involved are known. For instance, at Elkin (N. cent. rect., Richmond quadrangle), the base of the Richmond formation (Src) is at about 850 feet on the south or dropped side, just west of the railroad. It is at practically the same elevation as the base of the Winchester (Sw) immediately adjacent on the north or raised side. For the base of the Richmond to be level with the base of the Winchester, it must have gone down past the full

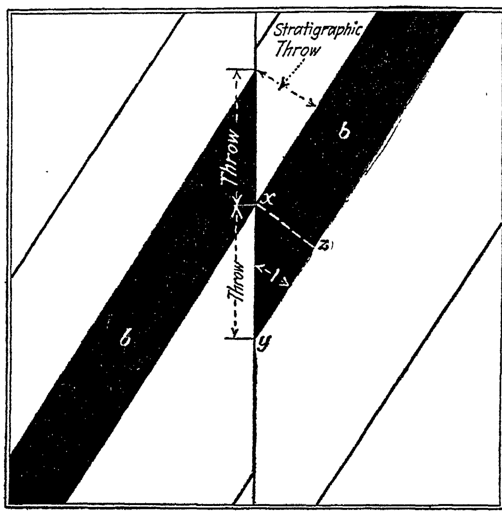


FIG. 40.—Throw and stratigraphic throw.

thickness of the Garrard sandstone (70 to 100 feet) and of the Winchester (200 to 230 feet), so that the throw is probably between 270 and 330 feet.

The same sources of error enter this as in the preceding problem, complicated with the variability of thickness of the formations involved.

Of course, if the beds are not horizontal, thickness of displaced beds is no longer equal to throw, as shown in Fig. 40, in which xz, the thickness of b, is, obviously, not equal to the throw xy

If the dip were known accurately, and also the thickness of beds displaced, the throw for a vertical fault could, of course, easily be computed, since

$$\angle 1 = 90° - \text{dip},$$
$$\text{and } \sin \angle 1 = \frac{xz \text{ (thickness)}}{xy \text{ (throw)}}.$$

This is of little or no value, however, on maps, inasmuch as the dips close to a fault plane are extremely variable, and are rarely shown on a map by dip arrows, and are not commonly determinable where not shown.

The horizontal components of fault movement may be resolved into one parallel to the strike of the fault, and one normal to the strike. Movement parallel to the fault trace cannot usually be recognized on a map, since there are no markers in the formations that permit of distinguishing various parts of them throughout their horizontal extent. The horizontal movement normal to the strike can usually be measured only when older beds have been thrust out some distance over younger formations, that is, in the low-angle thrusts.

The Rome folio (No. 78) furnishes about the best available map from which to work out the amount of overthrust. Considering the main fault, which intersects the north border of the map 1⅛ inches west of the northeast corner, and may be traced continuously to the center of the west border, we find its extreme sinuosity to be its most striking character. Throughout the distance, the Conasauga formation (Ꞓc) rests on younger beds, the whole overthrust being thrown into a series of folds, erosion of which has produced the irregular outline. The patch of Conasauga at Sand Springs (cent. rect.) is, obviously, a portion of the overthrust down-folded into a syncline, and nearly isolated by erosion. Since these patches are more numerous, bordering the main fault trace than further northwest, it is logical to assume that the fault dips, in general, to the southeast, and that the thrust came from that direction, the translated block of older formations moving to the northwest over younger beds. If

that is the case, the patch of overthrust material at Sand Springs came from the vicinity of Rome, or even farther southeast, and could not possibly have moved a less distance than from the main fault trace just west of Rome to the same fault trace northwest of Sand Springs, a distance of at least 4.3 miles. This is placing the overthrust at the lowest possible limit.

If a straight line be drawn from the northeast to the southwest ends of this fault, and it be assumed that everything southeast of this was once covered by the overthrust block, the distance from this strike line to the present fault trace at Rome is about 10 miles. It is probably safe to say that this comes nearer the truth than the smaller figure, though, of course, it is not attended with any such degree of certainty as the first and more obvious determination.

A much more complicated case occurs on the Roan Mountain quadrangle (Folio 151). The main overthrust intersects the east border of the map nearly 2 inches south of the east end of the twenty minute parallel. It may be traced in an irregular line, southwest past Pardee Point, McKinney Gap, Beauty Spot, and Whiteoak Flats, to Kittyton. There it loops back to the northeast, passing just west of Fordville, Fishery, and Marbleton, where it begins another loop, swinging back to a southwest trend, and leaving the west border of the map ½ inch north of the west end of the ten minute parallel. The sinuosity of this, as of the Rome fault, is the result of later folding, the big loop enclosing Buffalo Mountain, in which older rocks rest on the Knox dolomite (ꞒOk), being a remnant preserved from erosion as the result of its synclinal structure.

As in the previous case, the general dip of the fault plane is to the southeast, the overthrust block having moved northwest. The strike is northeast, and a line from Whiteoak Flats (SW. rect.) northwest to the point where the fault leaves the map crosses the trace three times, the extreme distance being 12 miles. It is plain, therefore, that this fault has a thrust of not less than 12 miles, though it may have been much more than this amount.

Additional maps suitable for determining the amount of fault movement

Amount of throw

68. Walsenburg folio, Colo.
95. Columbia folio, Tenn.
119. Fayetteville folio, Ark.-Mo.
186. Apishapa folio, Colo.
202. Eureka Springs-Harrison folio, Ark.-Mo.

Amount of thrust

20. Cleveland folio, Tenn.
27. Morristown folio, Tenn.
59. Bristol folio, Va.-Tenn.
75. Maynardville folio, Tenn.
196. Philipsburg folio, Mont.

Map of Glacier National Park (U. S. Geol. Survey, Bull. 600, Pl. XIII).

TYPES OF FAULTING

Two general lines of evidence may be used on maps in determining the type of faulting: (1) the dip of the fault plane, and (2) the strike of the fault planes with respect to each other and with respect to the strike of the rock formations.

Dip of Fault Plane

Maps

27. Morristown folio, Tenn.
75. Maynardville folio, Tenn.
196. Philipsburg folio, Mont.

Map of Glacier National Park (U. S. Geol. Survey Bull. 600, Pl. XIII).

If a dipping fault plane intersects an irregular topography, the trace will be irregular, and will follow the laws of "V's" (p. 227–228) for ordinary sedimentary formations. In other words, a low-angle fault plane will show distinct reentrants wherever cut by stream valleys. The steeper the plane the shorter the "V", which will disappear with a vertical fault.

With faults, as with rock formations, however, absence of "V's" for reasons already elaborated (pp. 224–225) does not mean verticality, but only steep dip.

The presence or absence of "V's" serves, then, on properly made maps, to classify faults as low-angle or high-angle. High-angle faults, it is now rather generally admitted, may be either normal or reversed, gravity or thrust. But low-angle faults, so far as known, are always reversed, and always thrust. Consequently, if any fault plane shows appreciable "V's" where its trace is crossed by valleys, it is a safe assumption that the fault is an overthrust.

This is especially well illustrated on the Morristown folio (No. 27). The fault nearest the north end of the ten minute meridian shows a whole series of crenulations where it is crossed by valleys. The "V" northeast of the reference line *B-B* is particularly striking. There, in a distance of 0.4 mile, measured normal to the general trend of the fault, the plane descends about 450 feet to the southeast, or a dip of a little over 1,100 feet per mile.

Another very notable example is the Lewis (or Chief Mountain) overthrust (see U. S. Geol. Survey Bull. 600, Pl. XIII). Every valley of any size that crosses the thrust plane produces a large reentrant. If the 6,500-foot strike line (p. 233) be drawn across Belly River, the drop from it to the apex of the "V" (elevation 4,700 feet) is 1,800 feet in a distance (normal to the strike line) of about 2.3 miles, or a dip of about 780 feet to the mile southwest.

The little "window" through the fault plane on Debris Creek (T. 30 N., Rs. 13 and 14 W.) might easily be interpreted as the result of anticlinal folding, but closer examination shows that it is more probably the result of change of gradient of the stream from steep to much flatter, according to the principle explained on pages 227–228. Nowhere along this "window" does the dip seem to be reversed, as in an anticline.

If fault planes show broad sweeping loops, of the sort that would be expected from the folding and planation of a gently dipping plane, it is also probably quite safe to assume low-angle

overthrusts. The loop in the fault between Lucilla and Friends in the southeast rectangle of the Maynardville folio (No. 75) is clearly the result of folding of a low-angle overthrust. The broadly looped fault in the southwest rectangle of the Philipsburg folio (No. 196) also gives clear evidence of overthrusting.

Under ordinary circumstances, the only faults that can be positively classified on an areal geology map are low-angle faults, recognized by the "V's" or by the folding of the fault plane. The absence of "V's" only means steep dips (pp. 224–225), and may result from gravity faults, or from high-angle thrusts.

Additional maps showing faults obviously low-angle thrusts

20. Cleveland folio, Tenn
59. Bristol folio, Va.-Tenn.
78. Rome folio, Ga.-Ala.
151. Roan Mountain folio, Tenn.-N. C.
Bull. 691, U. S. Geol. Survey, Pl. XXIV.

Relation of Faults to Folds

Maps

20. Cleveland folio, Tenn.
46. Richmond folio, Ky.
59. Bristol folio, Va.-Tenn.
95. Columbia folio, Tenn.
111. Globe folio, Ariz.
119. Fayetteville folio, Ark.-Mo.
196. Philipsburg folio, Mont.
Ste. Genevieve Co., Mo. (Mo. Bur. Geol. and Mines).

Thrust faults, which are usually of the so-called reversed type, are the results of intense compressive forces, and are likely, therefore, to accompany intense folding, especially of the overturned type. Since the same compression that produced the folds in most cases also produced the faults, there is a strong tendency for faults of this character to be parallel to each other and to the strike of the folds. This relation is typical of Appala-

chian structure, and one would not hesitate, from the map alone, to say that the faulting of the Cleveland (No. 20) or Bristol (No. 59) folios is dominantly thrust.

On the other hand, the presence of a large number of short faults, ranging through a great diversity of strikes and apparently not related to the folding, is highly indicative of gravity, tensional, or torsional forces, and of faults of the so-called gravity type, commonly normal. They are almost invariably high-angle faults. Accompanying such a disturbance there will be local compression, of course, and while, for example, the faults in T. 5 N., R. 12 W., Philipsburg folio (No. 196) appear to be dominantly normal, it would be practically impossible from the map alone to say how many of them, or which ones, are of the reversed type, or are produced by thrust, though a study of the structure section sheet and legend shows that some of them have been so interpreted in the field. The same may be said of the intricately faulted area of the Globe folio (No. 111), where the majority of the faults are, obviously, normal. It would be quite unsafe to conclude, however, that no thrusts occur in the district.

In general, compression sufficient to produce great overthrusting is likely to show its effects also in considerable folding and crumpling of the rocks. It is true that some of the greatest overthrusts are not associated with close folding of the Appalachian type. Still, there is in all cases sufficient warping of the rocks so that they do not appear on the map as a great area of undisturbed beds. In regions, therefore, where the rocks outside the immediate fault zones are almost or quite undisturbed, it would seem safe to assume that most of the faulting is gravity, with normal relations. Of course, in an intricate zone like that shown on the map of Ste. Genevieve County (see Mo. Bur. Geol. and Mines), the unequal settling of blocks may produce local compression, and minor thrusting, but the zone would certainly be interpreted as dominantly normal. So also with areas like the Columbia folio (No. 95) of Tennessee, the Fayetteville folio (No. 119) of Arkansas, or the Richmond folio (No. 46) of Kentucky.

As a supplementary exercise, study the type of faulting on the following maps:

24. Three Forks folio, Mont.
33. Briceville folio, Tenn.
65. Tintic special folio, Utah.
98. Tishomingo folio, Okla.
112. Bisbee folio, Ariz.
154. Winslow folio, Ark.-Okla.
170. Mercersburg-Chambersburg folio, Pa.
175. Birmingham folio, Ala.
Bull. 751, U. S. Geol. Survey, Pl. XIII.

EFFECT OF FAULTS ON OUTCROP

Effect on Nearly Horizontal Beds

Maps

36. Pueblo folio, Colo.
122. Tahlequah folio, Okla.
171. Engineer Mountain folio, Colo.

In horizontal formations, the effect of a fault on the distribution of the rocks and on the shape of the outcrops depends on the amount of throw, the thickness of the formations, and the degree of dissection of the region.

If the throw is less than the thickness of the uppermost formation, and erosion has not removed too much, the same formation may outcrop continuously on both sides throughout its length. Such a fault is present in the southwest rectangle of the Pueblo folio (No. 36).

Where a fault crosses a hill, the highest formation exposed is narrowed on the upthrown side of the fault. This is shown in the south third of the central rectangle of the Engineer Mountain quadrangle (Folio 171), in the behavior of the patches of Cutler formation (Cc) capping the divides. On the other hand, the lowest outcrop in a valley is widened on the upthrown side, as exemplified in the south central rectangle of the Pueblo sheet (Folio 36), by the widening of the Dakota formation on the southwest (raised) side of the fault that crosses St. Charles River.

Sometimes small inliers of older rock are exposed in the valleys on the upthrown side, as illustrated in T. 13 N., R. 23 E. of the Tahlequah folio (No. 122).

Ordinarily, if the throw is considerable, one or more formations are "cut out", that is, fail to outcrop, as where the Boone (Cbn) is faulted against the Winslow (Cwl) in T. 15 N., R. 22 E., on the Tahlequah quadrangle. On the other hand, an outcrop may be repeated, provided the topographic slope is favorable, as in sec. 18, T. 14 N., R. 23 E., on the same map, where, in following the reference line *B-B*, one goes uphill over two belts of the Morrow formation (Cmr). With horizontal beds, this can, of course, happen only on a hillside.

Other maps illustrating the behavior of faults in areas of nearly horizontal rock

46. Richmond folio, Ky.
68. Walsenburg folio, Colo.
95. Columbia folio, Tenn.
119. Fayetteville folio, Ark.-Mo.
132. Muscogee folio, Okla.
154. Winslow folio, Ark.-Okla.
186. Apishapa folio, Colo.
202. Eureka Springs-Harrison folio, Ark.-Mo.

Dip Faults and Offset

Maps

48. Tenmile folio, Colo.
193. San Francisco folio, Cal.

If an area is folded, any faults present may be classified according to their relation to the strike of the region, as (1) strike faults, if the trace of the faults is essentially parallel to the strike of the formations; (2) dip faults, if the trace of the faults is almost normal to the strike of the beds, that is, parallel to the direction of dip; and (3) intermediate, if the strike of the faults varies appreciably from either of the two above-named positions.

The effect of a dip fault, cutting dipping beds and eroded to a plane surface, is to shift the outcrop on the upthrown and

more eroded side in the direction of dip, that is, to produce offset of the outcrop at right angles to the strike of the formation (Fig. 41). Naturally, on the upthrown and more eroded end of an anticline cut by a dip fault, the effect will be to shift the outcrops on each limb in the direction of dip, that is, away from each other, so that the central outcrop is widened or possibly even split in two, showing a new central outcrop of an older bed (Fig. 42 and p. 271). Quite the contrary, on a syncline cut by a dip fault, the outcrops will be shifted toward each other, narrowing the central

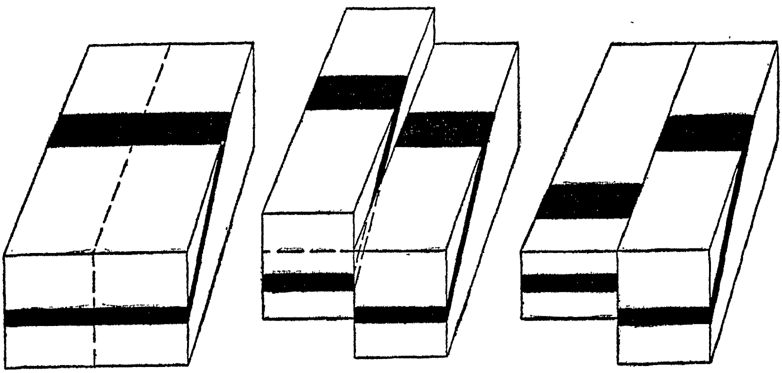


Fig. 41.—Dip fault producing offset.

belt; or the central outcrop may be completely removed, allowing the two adjacent lateral belts to coalesce into a single outcrops (Fig. 43 and p. 271).

The amount of offset, the dip being constant, will increase with the throw. The throw being constant, it will be greatest with low dips, and decrease as the dips increase.

A good example of the effect of a dip fault on dipping beds is to be seen on the Tenmile folio (No. 48). The fault about ¾ inch north of the intersection of the reference lines *C-C* and *K-K* cuts two sills of the Elk Mountain porphyry (Emp) at right angles to the strike, each sill being distinctly offset. Since the sills dip northeast, and since the upthrown side of a fault suffers the most erosion, shifting the outcrop in the direction of

dip, it follows that the south side, which has been shifted farthest northeast, is upthrown.

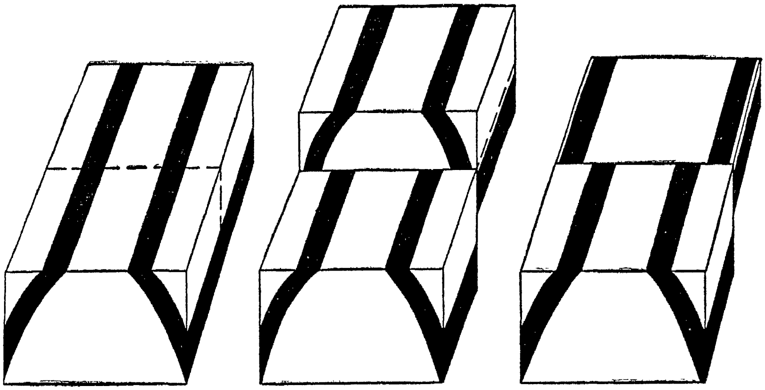


FIG. 42.—Effect of dip fault cutting anticline.

Another example occurs on the Concord quadrangle (Folio 193), in the pair of faults about 1½ inches north and the same distance west of the southeast corner of the map. They both

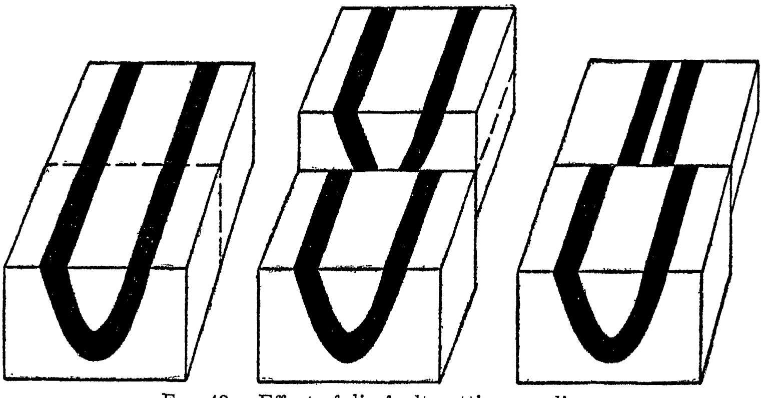


FIG. 43.—Effect of dip fault cutting syncline.

produce offset in the outcrop of the San Pablo formation (Tsp). Since the beds are dipping southwest, the upthrown side of each fault will have the outcrop shifted farthest in that direction,

showing that the block between the faults dropped, which has the same effect as though the outside area were raised.

Other examples of dip faults producing offset

65. Tintic special folio, Utah (fault nearest NW. cor. of map).
142. Cloud Peak-Fort McKinney folio, Wyo. (sec. 17, T. 51 N., R. 83 W.).
166. El Paso folio, Tex. (two faults N. of final "n" of "Mt. Franklin", N. line W. cent. rect.)
192. Eastport folio, Maine (at "t" of "Leighton Neck", intersection ten minute meridian and fifty-five minute parallel).
196. Philipsburg folio, Mont. (sec. 28, T. 5 N., R. 12 W.).
199. Silver City folio, N. M. (sec. 27, T. 18 S., R. 15 W.).
203. Colorado Springs folio, Colo. (secs. 2 and 3, T. 16 S., R. 67 W.).

Strike Faults

Repetition of Beds.—

Maps

20. Cleveland folio, Tenn.
78. Rome folio, Ga.-Ala.

If dipping beds are cut by a strike fault, the formations may be repeated, in which cases they remain in the same order

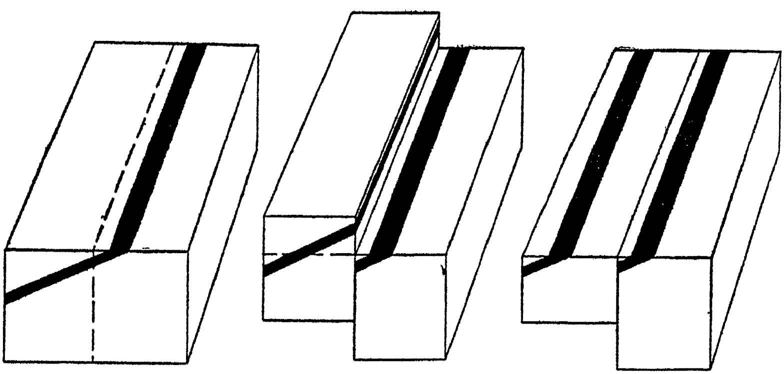


Fig. 44.—Strike fault causing repetition of outcrop.

(Fig. 44); whereas repetition from folding reverses the order of beds on opposite sides of a fold (Fig. 35).

An excellent example of repetition by faulting occurs on the Rome folio (No. 78) along reference line *C-C*, northwest of Wax, where the same formations are repeated in the same order by three successive faults. An even more striking series of repetitions occurs in the north central rectangle of the Cleveland folio (No. 20). In both cases the beds are dipping southeast, the southeast side of each fault being upthrown.

Other maps showing strike faults producing repetition of beds

12. Estilville folio, Ky.-Va.-Tenn.
27. Morristown folio, Tenn.
33. Briceville folio, Tenn.
75. Maynardville folio, Tenn.
151. Roan Mountain folio, Tenn.-N. C.

Cutting Out of Beds.—

Maps

24. Three Forks folio, Mont.
35. Gadsden folio, Ala.

A strike fault may cut out the outcrop of beds (Figs. 45 and 46). An excellent illustration occurs on the Gadsden folio

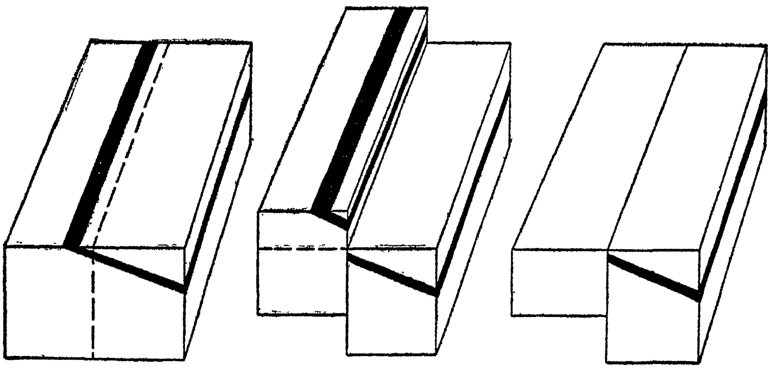


FIG. 45.—Strike fault causing failure to outcrop.

(No. 35). At Walnut Grove (S. cent. rect.) is a belt of Chickamauga limestone (Sc) along the northwest flank of a prominent

anticline. The formation does not outcrop on the southeast flank, because of a thrust fault. Another case clearly showing the same feature occurs on the Three Forks folio (No. 24).

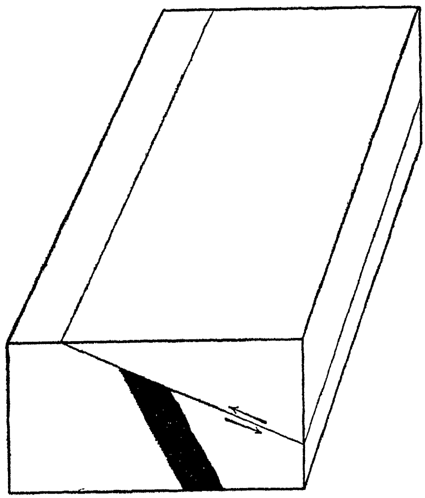


FIG. 46.—Strike fault (overthrust) causing failure to outcrop.

The outcrop of several beds is eliminated from the northeast flank of the syncline at the intersection of the reference line *C-C* with the thirty minute parallel.

Other maps showing examples of outcrops eliminated by strike faults

8. Sewanee folio, Tenn. (NW. flank Sequatchie anticline).
21. Pikeville folio, Tenn. (NW. flank Sequatchie anticline).
36. Pueblo folio, Colo. (SW. cor., between the Archean and the Morrison).
75. Maynardville folio, Tenn. (SE. flank Poor Valley Knobs syncline, E. cent. rect.).
179. Pawpaw-Hancock folio, Md.-W. Va.-Pa. (NE. rect., NW. flank of anticline at Keefer Mountain).

Intermediate Faults

Offset with Overlap.—

Maps

48. Tenmile folio, Colo.
192. Eastport folio, Maine.

If the throw is such that a strike fault would produce repetition of beds, then an intermediate fault will produce the relation known as offset with overlap (Fig. 47), the offset being the amount of apparent shifting of the outcrop normal to the strike, the overlap being the amount the ends of the faulted bed appear to lap past each other. Throughout part

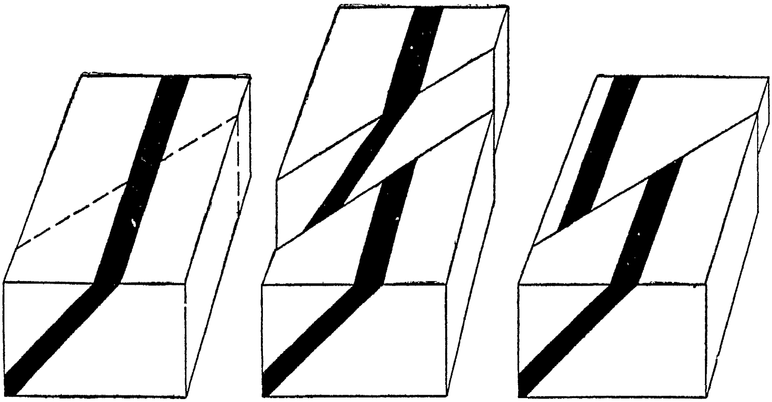


FIG. 47.—Intermediate fault, producing offset with overlap.

of the length of the outcrop there is actual repetition of the bed. It is to be noted that this relation can be produced by a perfectly vertical fault, with only vertical movement. Of course, on a map, it is rarely possible to be sure that some of the apparent shifting is not due to a horizontal component. Where a fault cuts a symmetrical fold, and the shifting of outcrop is equal in amount and in opposite direction on the two flanks, lateral movement has, obviously, not been a factor, but not often is there evidence to rule out the possibility of lateral movement.

The amount of overlap varies with the angle between the strike of the fault and the strike of bed, being zero with a true dip fault, and increasing as the fault approaches the strike position. It is also affected by the throw of the fault and by the dip of the beds, increasing as the throw increases and decreasing as the dip steepens (Fig. 48).

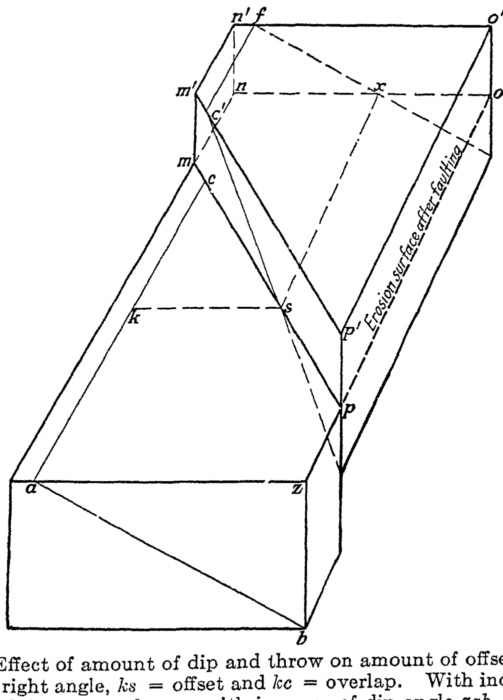


FIG. 48.—Effect of amount of dip and throw on amount of offset and overlap. Since *skc* is a right angle, *ks* = offset and *kc* = overlap. With increase of throw *mm′* these both increase, whereas with increase of dip angle *zab*, both decrease.

An excellent illustration of offset with overlap is to be found on the Tenmile folio (No. 48), near the intersection of the reference lines *L-L* and *E-E*. Both faults produce offset with overlap on the limestone bed at the contact of the Maroon (Cmr) and Wyoming (Jw) formations. Since Carbonate Hill is a syncline, the beds presumably dip west. If so, the northwest side of

each fault has been raised, since the outcrop is shifted farthest in the direction of dip (west) on the northwest of each fault. Just east of the belt of limestone is a porphyry sill, which also shows offset with overlap, though the amount of offset has not been great enough to separate the faulted ends of the dipping bed completely.

Several good examples occur on the Eastport folio (No. 192), an especially striking one being found just east of Pughole Mountain (SW. rect.).

Other maps showing offset with overlap

50. Holyoke folio, Mass.-Conn. (fault through "o" of "Holyoke Range," E. cent. rect.).
65. Tintic special folio, Utah (fourth and fifth faults from NW. corner of map).
161. Franklin Furnace folio, N. J. (S. line NE. rect.).
166. El Paso folio, Tex. (Mundy's Springs, NW. rect.).
179. Pawpaw-Hancock folio, Md.-W. Va.-Pa. (E. flank of anticline, SE. rect.).
193. San Francisco folio, Cal. (N. cent. rect. Concord sheet, SW. flank of syncline).
215. Hot Springs folio, Ark. (sec. 1, T. 4 S., R. 20 W.).

Offset with Gap.—

Maps

161. Franklin Furnace folio, N. J.
192. Eastport folio, Maine.
193. San Francisco folio, Cal.

If the throw is such that a strike fault would result in cutting out of beds, an intermediate fault will produce offset with gap (Fig. 49), the gap being the apparent separation of the ends of the faulted outcrop, measured parallel to the strike. Gap, in other words, is a special case of cutting out of beds, the outcrops being cut out for only a part of the distance, the length of which is greatest in faults approaching most closely the strike position, and becomes zero with the dip position. The amount of gap also increases with increased throw and

decreases with steeper dips in a manner analogous to overlap (see Figs. 48 and 50).

As in overlap, gap may result from vertical movement only, though ordinarily on a map there seems to be no way to rule out the possibility of some lateral movement.

Offset with gap is well illustrated on the Eastport folio (No. 192) by the fault cutting the three parallel belts of Sesh (SW. rect.) straight west of Yellowbirch Mountain. If the end of one belt be compared with the main part of another, the case

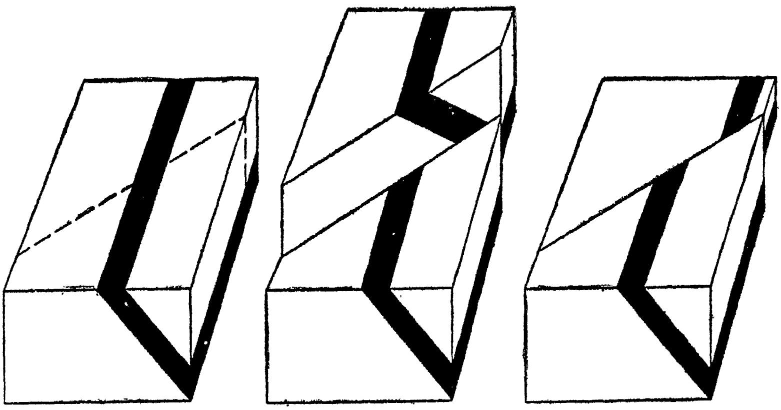


FIG. 49.—Intermediate fault, producing offset with gap.

may look like overlap, but if each belt is studied separately each is seen to have definite gap.

The small fault cutting the Jacksonburg limestone (Oj) in the west central rectangle of the Franklin Furnace quadrangle (Folio 161) produces offset with gap.

On the Concord quadrangle (Folio 193), a syncline is cut by an intermediate fault. The amount of offset is not enough to separate the ends of the faulted outcrops, so the relations are not so obvious as they might be. Nevertheless, they are sufficiently clear to show that: (1) the upthrown end of the syncline. from which most has been eroded, has its central outcrop narrowed; (2) its lateral outcrops shifted in opposite directions

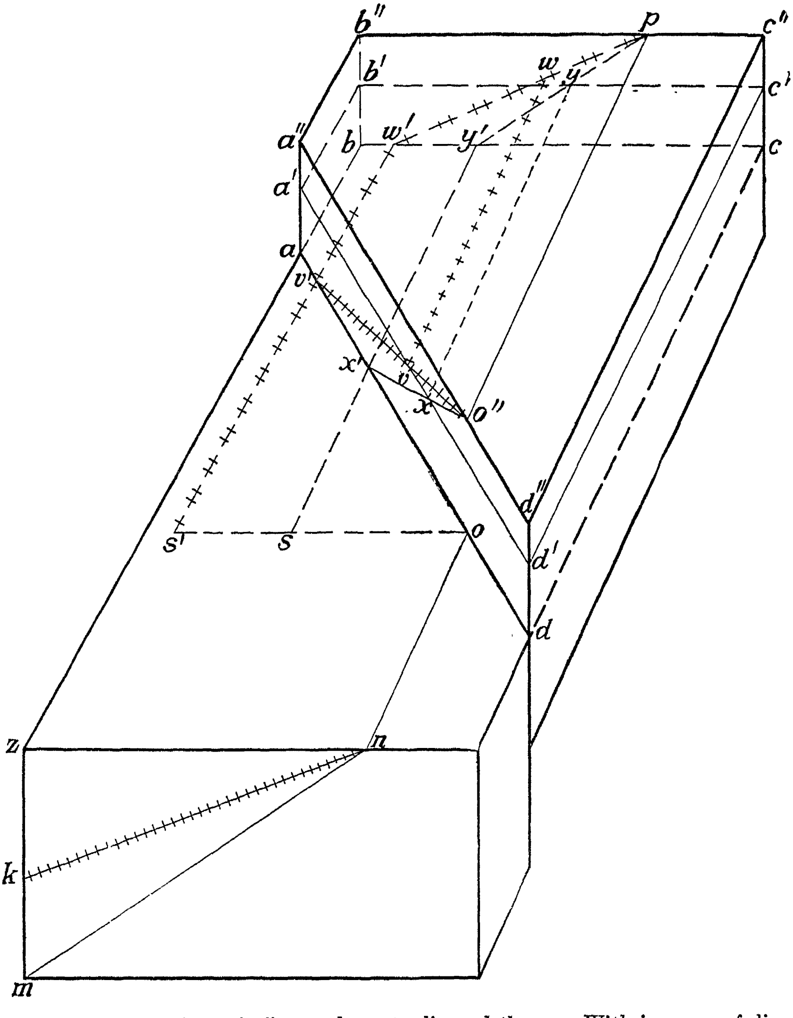


FIG. 50.—Relations of offset and gap to dip and throw. With increase of dip from *znk* to *znm*, offset decreases from *os'* to *os* and gap from *s'v'* to *sx'*. With decrease of throw from *aa''* to *a'a''*, offset and gap obviously decrease.

toward each other; (3) the result of the shifting in opposite directions being to produce offset with overlap on one flank (SW.) and offset with gap on the other (NE.).

Here, it is obvious that the movement has been chiefly vertical, since the outcrops are shifted in opposite directions, which would not be the case were the movement horizontal and parallel to the fault trace.

Had the syncline been overturned, with both flanks dipping in the same direction at the same angle: (1) neither end of the syncline would have been narrowed; (2) the offset would have been in the same direction on both flanks; and (3) both flanks would have shown offset with overlap, or else both offset with gap.

Additional maps showing offset with gap

50. Holyoke folio, Mass.-Conn. (Jhp in S. cent. rect.).
65. Tintic special folio, Utah (second and third faults from NW. cor. of map).
142. Cloud Peak-Fort McKinney folio, Wyo. (sec. 10, T. 50 N., R. 83 W.).
196. Philipsburg folio, Mont. (Cent. rect., fault extending S. from "F" of "Flint").
207. Deming folio, N. M. (Fluor Camp, N. cent. rect.).

Faults with Diminishing Throw

Maps

98. Tishomingo folio, Okla.
170. Mercersburg-Chambersburg folio, Pa.

Figure 51 shows the effect of decreasing throw on a strike fault with dipping formations. In the diagram, the result is attained with a vertical fault plane, and vertical movement only. On a map it is not often possible to say whether the case is so simple, but essentially the same effect, at least, is to be seen in the southwest portion of the Mercersburg quadrangle (Folio 170).

A somewhat similar relation is to be observed on the Tishomingo quadrangle (Folio 98), in T. 2 S., R. 5 E. This, of course,

might result from a fault cutting across an already existing fold, but is more likely to be caused by variation in throw, along the strike of the fault.

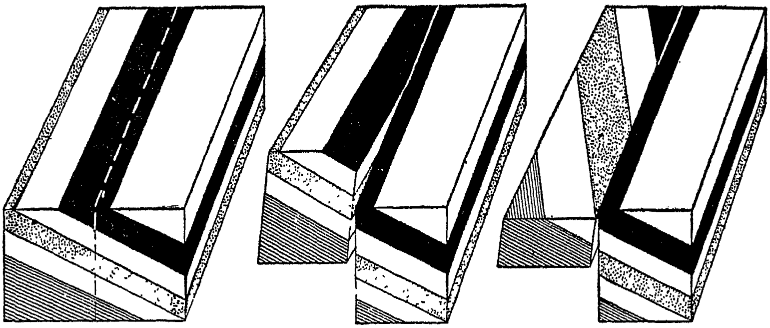


FIG. 51.—Effect produced by strike fault wth diminishing throw.

Additional examples that might be interpreted in a similar manner are listed below:

142. Cloud Peak-Fort McKinney folio, Wyo. (T. 51 N., R. 83 W.).
175. Birmingham folio, Ala. (sec. 25, T. 17 S., R. 1 E.).
196. Philipsburg folio, Mont. (just NE. of Twin Peaks, E. cent. rect.).

AGE OF FAULTING

Maps

24. Three Forks folio, Mont.
56. Little Belt Mountains folio, Mont.
98. Tishomingo folio, Okla.
183. Llano-Burnet folio, Tex.

As with the date of folding, that of faulting lies somewhere between the age of the youngest rock faulted and that of the oldest undisturbed bed above, or concealing, the fault. On the Burnet quadrangle (Folio 183), for instance, several of the faults cut the Smithwick shale (Cs) of Carboniferous age, and are concealed (fine dots, not dashes) by the Trinity formation (Kt) of the Comanche series. These particular faults, and, by inference, the other faults of the region, are, therefore, post-Penn-

sylvanian (or better post-Smithwick) and pre-Comanchean (pre-Trinity).

By the same reasoning, the large fault through the center of the Three Forks sheet (Folio 24) is post-Laramie, pre-Bozeman. Since at least one fault in the northwest corner of the map cuts the Livingston and is buried by the Bozeman, it is generally inferred that the faulting is post-Livingston, and pre-Bozeman.

It sometimes happens, however, that faults of two generations can be identified on a map. Several of the faults on the Tishomingo folio (No. 98) clearly cut the Franks conglomerate (Cf) and are, therefore, later than that formation. One fault, however, in sec. 22, T. 1 S., R. 3 E. is shown by the customary symbol of fine dots, to be concealed beneath the Franks, therefore being of an older generation, the fault being planed down by erosion before the Franks was deposited. Of this fault, it can be definitely concluded that it is post-Caney (Ccy) and pre-Franks, provided the field work is correctly done.

The long fault that terminates in sec. 3, T. 4 S., R. 5 E. cuts nothing younger than Caney, and is concealed by the Trinity. It is, therefore, post-Caney, and pre-Trinity, but, for all the evidence thus far noted, might belong to either generation referred to above. Since, however, it is a very long fault, parallel to the general strike, and to the faults that cut the Franks, it is probably (though not definitely) of the later generation.

Occasionally, faults are shown in full, when they should be dotted to indicate that they are buried. Such is almost certainly the case of the fault just northeast of White Sulphur Springs on the Little Belt Mountains sheet (Folio 56). Since on one side of the fault the Smith River lake beds (Ns) rest on the Belt series (Ab) of Algonkian age and on the other on beds as young as the Quadrant (Cq) of Pennsylvanian age, the fault was, obviously, formed and planed down before the lake beds were deposited. Unless there has been later movement along this old zone the fault should be shown as concealed below the Smith River lake beds.

Additional maps suitable for determining the age faulting

79. Atoka folio, Okla. (T. 3 S., R. 9 E.).
120. Silverton folio, Colo. (intersection C-C and thirty-five minute meridian).
142. Cloud Peak-Fort McKinney folio, Wyo. (T. 51 N., R. 83 W.).
166. El Paso folio, Tex. (NW. corner).
194. Van Horn folio, Tex.

IGNEOUS ROCKS

INTRUSIVES

Batholiths and Bosses

Maps

11. Jackson folio, Cal.
142. Cloud Peak-Fort McKinney folio, Wyo.
196. Philipsburg folio, Mont.

Batholiths and bosses bear very irregular relations to adjacent intruded formations, the walls of such intrusives usually being steep, the depth of the body very great, and its size considerable. Such features often make it possible to recognize these larger intrusives with some certainty on geologic maps. On the Jackson quadrangle (Folio 11), for instance, the largest body of granodiorite (Grd, NE. rect.) does not seem to bear any relation whatever to the distinctly erratic dips in the adjacent rocks. Furthermore, its walls are obviously steep, since its border contact is not shifted at all by the deep canyon of the North Fork of Mokelumne River. These conditions alone constitute a good reason for calling the body a large boss or small batholith. The further facts that granodiorite is an intrusive type, and that this particular rock is shown in the legend to be younger than the adjacent sediments, are entirely consistent with this interpretation. By way of contrast, the andesite (Na) is clearly seen to be unrelated to the folding, to cap divides, and to be completely cut through by the deeper valleys. These features would point to an extrusive rock, a conclusion borne out by the statement in

the legend that it is partly fragmental, that is, in the form of flows and tuffs.

Another interpretation, however, which may possibly suggest itself for the granodiorite is that it might be an older batholithic mass, buried unconformably beneath the Calaveras (Cc). The great steepness of the contact, where it is cut by the North Fork Canyon, is rather out of harmony with its being an old land surface, particularly when it is noted that these slopes are steep on all sides of the body, whereas the adjacent sediments have a variety of high dips, that would demand great distortion of any earlier granite mountain.

A very similar illustration is to be seen in the large masses of granodiorite (Tgd) on the Philipsburg quadrangle (Folio 196). The same lack of relation of the igneous mass to the dips of the adjacent rocks, and the same steepness of contact, betrayed by the lack of "V's" in its border, at stream valleys, is quite sufficient evidence of its batholithic character. The striking way in which it cuts off folds and faults is added evidence of great importance, and leads to a certain conclusion that in this case the batholith (or boss) is not an older one buried unconformably, but is intruded into the now contiguous rocks.

The large area of granite on the Fort McKinney quadrangle (Folio 142) is, obviously, from its great extent and granitic character, a batholith; but in this case it is also plain, not only from its pre-Cambrian age (legend), but as well from its map relations, that it is older than the adjacent sediments. The long, narrow, and unbroken belt of Deadwood formation (Ꞓd) must have been laid down on top of the granite. Had it been deposited first, the granite intrusion, miles in extent, would not everywhere have stopped at the exact horizon of this formation, but would in places have penetrated to higher horizons, while in other places it would not have reached so far. Furthermore, the large number of dikes cutting the granite, none of which enter the sediments, though some of them stop abruptly at the contact, are evidence that the granite batholith is the old basement, exposed by erosion long before Deadwood time.

Other maps illustrating batholiths and bosses

24. Three Forks folio, Mont.
43. Bidwell Bar folio, Cal.
56. Little Belt Mountains folio, Mont.
98. Tishomingo folio, Okla.
141. Bald Mountain-Dayton folio, Wyo.
173. Laramie-Sherman folio, Wyo.
203. Colorado Springs folio, Colo.

Laccoliths

Maps

127. Sundance folio, Wyo.-S. D.

Unlike batholiths, laccoliths show rather definite relations to the adjacent walls, the sedimentary rocks dipping outward as in a dome. The contact between the igneous and sedimentary rock likewise dips out at a moderately low angle. This is shown beautifully on the Sundance sheet (Folio 127), in which the dips about the laccolithic cores are indicated not only by dip and strike arrows, but also by striking development of "V's" on all streams draining from the central upland. Numerous "V's" pointing downstream show that the beds dip downstream more steeply than the stream gradient. Such "V's" occur not only in the sedimentary contacts, but in the contact as well between the central igneous core and the sedimentary wall, proving that this contact dips outward at a low angle. This is most characteristic.

Green Mountain (N. cent. rect., Sundance sheet) is doubtless a similar laccolithic mountain, which has not yet been sufficiently eroded to show the igneous core. The many "V's" in the contacts about Green Mountain often puzzle the beginner, because no streams or valleys are shown corresponding to their position. The explanation is quite probably to be found in the poor topographic mapping, the valleys which actually occur at these "V's" having been overlooked by the topographer.

The long narrow belts of Deadwood formation (€d) shown within the area of igneous core of Bear Lodge Mountains are

another evidence of their laccolithic character, and represent the interfingering of the laccolithic margin with the sedimentary beds (Fig. 52).

Good maps showing characteristic laccolithic structure are rare. Fine examples are shown in the Twenty-first Annual

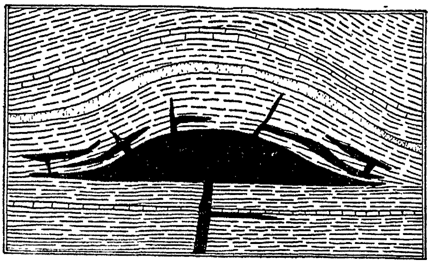


FIG. 52.—Laccolith with accompanying dikes and sills.

Report of the United States Geological Survey, Part III, Plates XX and XLI. The Aladdin folio (No. 128) shows them in less perfect development (SW. rect.).

Dikes and Sills

Maps

24. Three Forks folio, Mont.
48. Tenmile folio, Colo.
56. Little Belt Mountains folio, Mont.
60. La Plata folio, Colo.
71. Spanish Peaks folio, Colo.
120. Silverton folio, Colo.

Dikes are tabular bodies of igneous rock, intruded along fractures, commonly more nearly vertical than horizontal, though they may occupy any position except one parallel to the bedding of stratified deposits. Sills, on the other hand, are insinuated along bedding planes, and are more commonly horizontal, or nearly so, though they may occupy any position up to the vertical or beyond, either because folded after intrusion or because intruded into already tilted strata.

The most striking sheet published showing these features is doubtless the Spanish Peaks folio (No. 71), in which the dikes are shown by long straight lines passing indiscriminately across formation contacts. This feature in itself shows they are not sills, and that they are clearly intrusive. The entire lack of "V's" where these dikes cross valleys is also characteristic, but only proves that they are dipping steeply. In a region where the sediments are nearly horizontal, however, this becomes evidence that they are dikes. Dikes are sometimes strikingly radiating, emanating from some igneous center, as shown on the above map, and also on the Little Belt Mountains folio (No. 56).

Many bodies of rock in the Spanish Peaks area, unlike the dikes, follow the contours, showing that they are essentially horizontal. Though horizontality is not in itself proof positive that the body is not a dike, the evidence of sill or flow is very strong. That these bodies are parallel to the sedimentary contacts is still more conclusive. It must be borne in mind, however, that they could be contemporary flows (extrusive) as well as sills, judged by their form alone, and it may often be impossible, on the map, to distinguish between the two. For example, the San Juan Tuff in the south central and southeast rectangles of the Silverton folio (No. 120) occupies a narrow belt following the contour lines closely, but cannot be an intrusive, as evidenced by its lithologic character.

Sills or buried flows in nearly horizontal position may outcrop in completely closed curves about mountain peaks. For example, see Jacque Mountain on the Tenmile folio (No. 48), or Hesperus Peak in the north central rectangle of the La Plata folio (No. 60).

Sills may occasionally break across from one horizon to another, instead of following a single bed. Extrusive sheets (lava flows) cannot well do this. The belts of diorite and monzonite porphyry (dmp) on either side of Mancos River in the northwest rectangle of the La Plata sheet (Folio 60) are clearly the outcrop of a sill rather than a flow, since they do not keep to a constant horizon.

A sill may sometimes send off subsidiary dikes into overlying beds, a feature, of course, impossible with buried flows. Such seems to be the case with the large patch of Lincoln porphyry (lp) on Eagle River (Tenmile folio, No. 48), which sends out a dike toward Chicago Mountain. A similar feature occurs on the horseshoe-shaped patch of diorite and monzonite porphyry (dmp) in the central rectangle of the La Plata folio (No. 60).

That sills may be folded is probably shown by those near the north end of the fifteen minute meridian on the Three Forks folio (No. 24), in which strips of red are sills occupying pitching folds along with the enclosing sediments.

Tilted sills or interbedded flows, if cut by valleys, follow the same rules for "V's" as ordinary sedimentary formations, and the amount of dip (pp. 240–242) may be worked out in favorable places. Thus, at Sugarloaf Gulch and Jacque Gulch, north central part of Tenmile District special map (Folio 48), the igneous bodies are dipping downstream (NE.) more steeply than the stream gradient, and the dip may be easily computed.

Additional maps showing dikes and sills

Dikes

58. Elmoro folio, Colo.
68. Walsenburg folio, Colo.
104. Silver City folio, Idaho.
130. Rico folio, Colo.
138. Redding folio, Cal.
141. Bald Mountain-Dayton folio, Wyo.
142. Cloud Peak-Fort McKinney folio, Wyo.
161. Franklin Furnace folio, N. J.
207. Deming folio, N. Mex.
215. Hot Springs folio, Ark.

Sills

58. Elmoro folio, Colo.
68. Walsenburg folio, Colo
130. Rico folio, Colo.
153. Ouray folio, Colo.
171. Engineer Mountain folio, Colo.

Contact Metamorphism

Maps

11. Jackson folio, Cal.
56. Little Belt Mountains folio, Mont.
71. Spanish Peaks folio, Colo.
196. Philpsburg folio, Mont.

Only the larger intrusives commonly produce metamorphic aureoles of sufficient breadth to represent on maps. Such a border is shown on the Little Belt Mountains folio (No. 56) and another on the Spanish Peaks folio (No. 71). On the other hand, intrusive bodies quite as large may not show any such border on the map. This is illustated by the patches of granodiorite (Tgd) on the Philipsburg folio (No. 196), and by those (grd) on the Jackson quadrangle (Folio 11). Although it is possible that differences in either the intrusive or the wall rock, or both, are responsible for a lack of contact effects, it is more probable that there is a lack of consistent practice in representing this feature on maps. A metamorphosed border shown on the map is evidence of contact change and, by inference at least, of intrusive bodies. Its absence on the map, on the other hand, probably does not prove the absence of metamorphism, but only failure to make record of it on the geologic sheet.

EXTRUSIVES

Maps

11. Jackson folio, Cal.
17. Marysville folio, Cal.
65. Tintic special folio, Utah.
151. Roan Mountain folio, Tenn.-N. C.
153. Ouray folio, Colo.
199. Silver City folio, N. M.
207. Deming folio, N. M.

The common forms of extrusives are cones, lava flows, and beds of ash or tuff. A geologic map of a typical cone is shown in the Marysville folio (No. 17). On the map, its most distinctive

feature is the conical shape of the hill, with the perfect development of radial drainage.

Very typical of flows and ashbeds is the andesite (Na) on the Jackson quadrangle (Folio 11). The description "fragmental" in the legend, of course, indicates that the rock is not an intrusive. Aside from this, however, its position capping divides (NE. rect.), the fact that it rests on a variety of other formations, and its discordance with the underlying rocks, point clearly to an extrusive rather than to a sill. The only way it could possibly be interpreted as a sill would be that it was insinuated along an angular unconformity, and later the overlying beds completely stripped away. While this would be theoretically possible, the extrusive explanation is much the simpler and more probable.

It is when extrusive sheets have been buried that their resemblance to sills becomes confusing. The amygdaloid bed in the Snowbird formation (Roan Mountain folio, No. 151) has all the appearance on the map of a typical sill and can only be distinguished as extrusive by the statement of its lithologic character given in the legend. It is a contemporary flow, buried under later accumulations of sediment.

On the Tintic special map (Folio 65), the Packard rhyolite (prh) and the andesite (an) are rather clearly not sills, because of their striking discordance with the underlying beds. It is not at all obvious, from the map alone, however, whether they overlie or cut the older beds, that is, whether they are deep-seated intrusive bodies or flows. There are, for example, no places where streams cut through these extrusives and expose the older beds beneath, or where the extrusives are clearly remnants occupying divides. Their character, however, is clearly stated in the legend.

The numerous flows listed in the legend of the Deming folio (No. 207) give little or no evidence of their extrusive character from the map alone. On the Silver City folio (No. 199), the andesite (Tan) obviously caps divides, and rests on a sufficient variety of rocks to make its extrusive character evident at once. The same relations exist for the rhyolite and latite (Trl),

though less obviously. Attention should be directed to the basal contact of Trl near Cameron Creek Basin (NE. rect.) where valleys cutting through it expose lower rocks and bear evidence that it is not a deep-seated mass. That it is not a sill is suggested by the large variety of rocks on which it rests, and its structural discordance on those rocks.

The San Juan tuff (Ouray folio, No. 153) is mapped with an igneous symbol (a pattern of triangles), but would be definitely recognized on a map as an extrusive by the fact that it caps uplands and rests with discordance on many older beds. That it is itself more or less stratified is shown clearly by the fact that it carries sills of latite (Tl and Tc).

Additional maps showing extrusive igneous rocks

52. Absaroka folio, Wyo.
58. Elmoro folio, Colo.
86. Ellensburg folio, Wash.
106. Mt. Stuart folio, Wash.
120. Silverton folio, Colo.
126. Bradshaw Mountains folio, Ariz.
139. Snoqualmie folio, Wash.
192. Eastport folio, Maine.

AGE OF IGNEOUS ROCKS

Maps

11. Jackson folio, Cal.
24. Three Forks folio, Mont.
48. Tenmile folio, Colo.
58. Elmoro folio, Colo.
60. La Plata folio, Colo.
68. Walsenburg folio, Colo.
71. Spanish Peaks folio, Colo.
120. Silverton folio, Colo.
141. Bald Mountain-Dayton folio, Wyo.
142. Cloud Peak-Fort McKinney folio, Wyo.
151. Roan Mountain folio, Tenn.-N. C.
153. Ouray folio, Colo.

173. Laramie-Sherman folio, Wyo.
192. Eastport folio, Maine.
196. Philipsburg folio, Mont.
199. Silver City folio, N. M.
207. Deming folio, N. M.

Igneous rocks may be dated (1) with respect to diastrophism, (2) with respect to other igneous rocks, and (3) with respect to contiguous sedimentary formations.

1. On the Silver City folio (No. 199), it is entirely obvious that the andesite and basalt flows (Tan) antedate the faulting which has displaced them in a very complex manner. The same is true on the Eastport folio (No. 192), most of the igneous rocks clearly being older than the faulting, which cuts and offsets them. If the mapping is correctly done, however, we must conclude that some, at least, of the intrusive masses of diabase (Sdb) are later than some of the faults. For example, at Pembroke (NW. part of map) a fault that distinctly offsets several formations does not seem at all to shift the mass of Sdb. A similar situation seems to obtain in other areas of this sheet. Between Orange Lake and Roaring Lake (SW. rect.) a tongue of Sdb seems to follow a fault plane for a short distance, as though the fracture were already there when the intrusion occurred. At Edgecome Point (E. central part) a mass of the diabase has clearly followed a fault that had previously offset Sl.

There are places, however, where the Sdb appears to be cut off by faults, as west of Garnet Point (N. cent. part). This may be explained in several ways. It may be quite possible that there are two or more periods of faulting, or two or more periods of intrusion. In either case, most of the faulting might precede the intrusion, but some faulting occur after some of the intrusion. Or it is possible that this case, and several others of similar appearance, represent intrusion of the diabase as far as the fault plane, against which it abutted and stopped.

On the Philipsburg quadrangle (Folio 196) the batholith of granodiorite (Tgd) in the central and east central rectangles appears very definitely to transgress the great overthrust as

well as some of the minor accompanying faults, and is, therefore, later than the dominant faulting of the region.

Sometimes one of two intersecting dikes appears to offset the other. Two or three intersections in the northwest rectangle of the Spanish Peaks sheet (Folio 71) seem to do this and an even plainer case occurs in the southeast corner of the Elmoro sheet (Folio 58). In this case the offset dike is the earlier, cut by a later fault along which still later material has been intruded. In similar manner, a dike may offset a sill, as in the southeast rectangle of the Ouray folio (No. 153), with the same significance.

The age of igneous rocks with respect to folding is less obvious. The sills on the Three Forks sheet (Folio 24) were probably intruded before the deformation and subsequently warped into the present pitching folds, although it is possible that they were insinuated along bedding planes already folded prior to the intrusion. The same applies to the tilted sills on the Tenmile special (Folio 48).

2. If one igneous rock cuts another, the relative ages are at once indicated. On the Deming folio (No. 207), for instance, the rhyolite porphyry dikes (Trp) are clearly younger than the granite (gr) into which they are intruded (SE. rect.). On the Walsenburg quadrangle (Folio 68) the dikes shown in red are clearly represented as cutting those shown in orange, and should be interpreted as the younger. This is in accord with their relative positions in the legend. On the Spanish Peaks folio (No. 71) three types of dikes are shown in red, purple, and orange stripes. Both the red and the purple are shown cutting the orange, the latter, therefore, being classed as the oldest of the three. The red, since it quite plainly cuts both the purple and the orange, is the youngest. This is consistent with their arrangement in the legend, where the orange is shown at the bottom and the red at the top of the igneous group.

On the La Plata quadrangle (Folio 60), dmp is clearly cut by sp, sy, and di, and is, therefore, older than each. The relations with mz are less clear, though the latter probably also cuts dmp. On the other hand, sp, sy, mz, and di do not appear

to be in contact one with another anywhere on the outcrop, so that, so far as this map is concerned, their relative ages can be known only from the legend, but cannot be worked out on the map.

Even where igneous rocks are in actual contact, their relations are not always evident on the map, although the field criteria might be clear enough. For example, on the Sherman quadrangle (Folio 173) the relative ages of the Sherman granite (shg) and the granite porphyry (gp) are very obscure. The more or less isolated masses of porphyry in the granite might be taken to mean separate intrusive bodies, whereas the field interpretation (text of folio) is that the porphyry occurs as inclusions in the more recent granite. Many such contacts will doubtless be encountered on maps, in which the age relations are indeterminate.

Of course, where extrusives overlie other igneous rocks, either intrusive or extrusive, the age relations are simple. For example, the andesite extrusive (Na) on the Jackson folio (No. 11) is clearly younger than the granodiorite (grd) intrusive on which it lies. On the Silverton folio (No. 120) the Silverton series (Ts) is younger than the San Juan tuff (Tsj) on which it rests, and the pyroxene andesite still younger. The andesite (Tan) of the Silver City folio (No. 199) clearly rests (N. cent. rect.) on the rhyolite (Trl), capping the divides, with the older rhyolite beneath. This is exactly the reverse of their ages as shown in the legend, but conforms to the description in the text. The two seem to be actually interbedded, and, therefore, partly contemporaneous.

3. Igneous rocks are dated in the geologic time scale by means of their observed relation to known sedimentary rocks. Extrusives which have subsequently been buried follow the law of superposition, that is, they are younger than the rocks on which they were laid and older than the rocks deposited upon them. For instance, the amygdaloid bed in the Snowbird (Ꞓsb) formation (Roan Mountain folio, No. 151) is younger than the lower and older than the upper beds of the Snowbird, and,

since that formation is Cambrian, so, of course, is the bed of igneous material.

On the other hand, a sill is, of necessity, younger than the sedimentary beds both above and below it; for instance, the sills intruding the Wyoming formation (Jw) on the Tenmile sheet (Folio 48) are clearly younger than the Wyoming, and pre-fault in age, but that is, at best, very indefinite. Of course, if an intrusive has been exposed by erosion, then buried by a higher bed, it is younger than the formation it intrudes, and older than the formation which rests on its eroded surface. On the Bald Mountain quadrangle (Folio 141), for instance, numerous dikes cut the granite (gr) but stop abruptly at the base of the Deadwood formation (Ꞓd). It is rather obvious that, had the Deadwood been present when the dikes were intruded, some at least of them would have penetrated it. Consequently, it must be assumed that the period of intrusion of the dikes had ended before Deadwood time—in other words, the dikes are post-granite and pre-Deadwood. This places them, from the data on the map alone, as either pre-Cambrian or early Cambrian.

The sills near the north end of the fifteen minute meridian on the Three Forks sheet (Folio 24) intrude the Montana (Kmc) and are buried beneath the Bozeman lake beds (Nb). They are, therefore, either late Cretaceous or early Tertiary.

On the Fort McKinney quadrangle (Folio 142) the granite may be safely assumed to be pre-Deadwood, because, had it been intruded after Deadwood time, so large a mass would surely have penetrated at some points to higher horizons (pp. 301 and 317), not everywhere stopping at a single definite formation.

Other maps suitable for dating igneous rocks

50. Holyoke folio, Mass.-Conn.
98. Tishomingo folio, Okla.
106. Mt. Stuart folio, Wash.
127. Sundance folio, Wyo.-S. D.
130. Rico folio, Colo.
183. Llano-Burnet folio, Tex.
193. San Francisco folio, Cal.
203. Colorado Springs folio, Colo.

UNCONFORMITIES

CRITERIA FOR RECOGNIZING UNCONFORMITY ON A MAP

Criteria of value for recognizing unconformity in the field are not always useful on maps. For instance, it is only rarely that a basal conglomerate serves on a map, and then only in conjunction with the legend, whereas in the field it may sometimes be an extremely valuable evidence. Even more rarely may old erosion surfaces be detected on a map as such, though their identification in the field is often possible. There are, however, numerous aids to the recognition of stratigraphic breaks, on geologic maps, and these will be discussed in the following paragraphs.

Discordance

Maps

11. Jackson folio, Cal.
24. Three Forks folio, Mont.
65. Tintic special folio, Utah.

Not all unconformities are angular, of course, but those that are may usually be recognized at a glance on the map. For example, on the Three Forks sheet (Folio 24), the older rocks are, obviously, highly folded, as indicated by the linear pattern of outcrops. On the other hand, the Bozeman lake beds, from their wide and irregular outcrops, may be inferred to be much more nearly horizontal. The discordance of dip involved in the unconformity at the base of the Bozeman is most striking. This discordance may exist as well at the base of a volcanic as of a sedimentary series. On the Tintic special sheet (Folio 65), the older sedimentary rocks show clear evidence of folding, and of the truncation of those folds by erosion before the Packard rhyolite (prh) was poured out. The rhyolite in this case is as truly unconformable on the older folded series as though it were a sedimentary formation.

The discordance may be quite as great, and yet be much less strikingly shown, as on the Jackson quadrangle (Folio 11).

On this sheet, the andesite (Na) is seen to be essentially horizontal (NE. rect.) by the way its base, in general, coincides with the contours. The Calaveras (Cc) on which it rests is highly folded, as shown by dip arrows, though the formation is so thick that the degree of folding is not rendered conspicuous by narrow belts, as on the Three Forks sheet.

Other maps showing discordance of dip

50. Holyoke folio, Mass.-Conn.
79. Atoka folio, Okla.
98. Tishomingo folio, Okla.
142. Cloud Peak-Fort McKinney folio, Wyo.
153. Ouray folio, Colo.
173. Laramie-Sherman folio, Wyo.

Missing Beds

Maps

20. Cleveland folio, Tenn.
56. Little Belt Mountains folio, Mont.
79. Atoka folio, Okla.
142. Cloud Peak-Fort McKinney folio, Wyo.

If beds of Cretaceous age, for example, rest on Carboniferous or older rocks with Triassic and Jurassic entirely missing, there is, obviously, a big gap in the stratigraphic column. Such is the case on the Atoka quadrangle (Folio 79). In this instance, the unconformity is made much more obvious by being angular. On the Fort McKinney quadrangle (Folio 142), however, the unconformity between the Bighorn limestone (Ob) and the Madison limestone (Cm) does not show a single one of the commoner and more obvious map evidences of unconformable relation, except that the Silurian and Devonian are wholly missing. In this case, the word "unconformity" in the legend would give the clue to the situation. On the Little Belt Mountains folio (No. 56), on the other hand, the legend does not carry a single statement of unconformity, though there are several breaks in the column. This is characteristic of many of the older maps. Another feature of the older maps is the absence of the term

"Ordovician". On the Cleveland folio (No. 20), for instance, the Silurian is shown resting directly on the Cambrian. This does not mean that the Ordovician is absent, but merely that it is included in the Silurian because at the time the map was made the term Ordovician was not in general use. This is no evidence at all of unconformity, because the Ordovician is not missing. There are actually several unconformities in the lower portion of this column, but the evidence is not to be found on the map.

Other maps illustrating unconformity shown by missing beds

24. Three Forks folio, Mont.
50. Holyoke folio, Mass.-Conn.
55. Fort Benton folio, Mont.
68. Walsenburg folio, Colo.
127. Sundance folio, Wyo.-S. D.
141. Bald Mountain-Dayton folio, Wyo.
173. Laramie-Sherman folio, Wyo.
183. Llano-Burnet folio, Tex.
203. Colorado Springs folio, Colo.

One Formation Resting on Several Formations

Maps

11. Jackson folio, Cal.
68. Walsenburg folio, Colo.
78. Rome folio, Ga.-Ala.
173. Laramie-Sherman folio, Wyo.

If one formation is seen to rest on several older ones it is good evidence that the older formations were exposed by erosion before the younger one was laid down. This is strikingly exhibited by the Chadron sandstone (Tc) of the Sherman quadrangle (Folio 173). The discordance in this case is also sufficiently striking to afford the best of evidence of the unconformable relation. On the Walsenburg folio (No. 68) the Nussbaum (Nu) rests on a number of older formations, and, though there is actual discordance between them and the younger rock, it is so slight as to be much less striking than on the Sherman sheet. The formation above the unconformity may be igneous, as with

the andesite (Na) on the Jackson quadrangle (Folio 11), but the relations remain the same.

One formation may also less commonly be found resting on several others because of overthrusting (pp. 279–280), as illustrated on the Rome folio (No. 78). In this case, however, the formations below are younger, not older, and the relation is commonly indicated by the fault symbol.

Other maps illustrating the above criterion

24. Three Forks folio, Mont.
50. Holyoke folio, Mass.-Conn.
98. Tishomingo folio, Okla.
120. Silverton folio, Colo.
166. El Paso folio, Tex.
183. Llano-Burnet folio, Tex.

Sediments Resting on Large Bodies of Igneous Rock without Metamorphism

Maps

98. Tishomingo folio, Okla.
141. Bald Mountain-Dayton folio, Wyo.
142. Cloud Peak-Fort McKinney folio, Wyo.

If large bodies of igneous rock intrude a sedimentary series, there is usually extensive contact metamorphism. If, on the other hand, sediments rest on a large body of intrusive igneous rock, and there is no metamorphism at the contact, and no dikes or stringers of the igneous rock extending out into the sediment, the natural inference is that this particular sediment was not there when the igneous rock in question was intruded. Since, however, it must have been intruded into something, and that something is no longer there, it is obvious that the intrusive must have been exposed by erosion, before its present sedimentary cover was laid down—hence unconformable relations.

This is admirably shown on the Tishomingo quadrangle (Folio 98). The Reagan sandstone (Єr) rests, over considerable areas, on the granite, but is not described in the legend as a quartzite or other metamorphic rock, but as a sandstone. The fact that it is

arkosic is added evidence of the erosion of the granite, before it was laid down. The contact of the Trinity (Kt) on the granite, obviously capping the hills with the granite exposed in the valleys between, affords another example of a sediment unconformable on a granite.

Another particularly striking example occurs on the Fort McKinney quadrangle (Folio 142). The Deadwood formation (Ꞓd), listed in the legend as sandstone, shale, and limestone, clearly non-metamorphic, rests everywhere on a huge mass of granite that must surely have metamorphosed it had the relations been those of intrusion. Obviously, the granite was intruded into some older rock, no longer there; this rock was stripped away by erosion, and the Deadwood deposited on the exposed and eroded surface of the granite.

This view is greatly strengthened by the entire absence of stringers of the granite penetrating the overlying beds, and by the fact that the granite is everywhere in contact with the Deadwood. According to the map, the latter does not much exceed 1,000 feet in thickness, and it is hardly to be assumed that a granite batholith of such size (Folio 141) should everywhere rise to this single formation as its roof.

Other maps illustrating the above principles

79. Atoka folio, Okla.
173. Laramie-Sherman folio, Wyo.
203. Colorado Springs folio, Colo.

Unmetamorphosed Rocks on Highly Metamorphosed Rocks

Maps

50. Holyoke folio, Mass.-Conn.

The intensity of metamorphism dies out gradually, and there should not normally be any sharp contrast between highly metamorphosed and unmetamorphosed rocks, if both series were present when the metamorphism took place. Such a sharp contrast, therefore, means a pronounced interruption in sedimentation. A very striking example is the Juratrias on the older rocks in the Holyoke folio (No. 50).

Other maps showing unconformity between a younger unmetamorphosed and an older metamorphosed series

24. Three Forks folio, Mont.
68. Walsenburg folio, Colo.
120. Silverton folio, Colo.
183. Llano-Burnet folio, Tex.

Truncated Faults

Maps

24. Three Forks folio, Mont.
142. Cloud Peak-Fort McKinney folio, Wyo.
194. Van Horn folio, Tex.

If, after formations have been displaced by faulting, the scarp has been removed by erosion, bringing both sides to the same level, and exposing beds of widely differing age on opposite sides, then, obviously, any formation laid down on this surface is notably unconformable with the older rocks (see also pp. 298 and 299). The Bolson deposits (Qb) of the Van Horn folio (No. 194) clearly bury such old peneplaned faults, and this is one of several map evidences of their unconformable position on the older formations. On this and all newer maps, such concealed faults are indicated by fine dotted lines. On some of the older maps (Three Forks folio, No. 24), on the other hand, the faults appear to end abruptly at the formation beneath which they are buried, as at the contact of the Bozeman lake beds. On the Fort McKinney quadrangle (Folio 142), the faults in sec. 17, T. 51 N., R. 83 W. are clearly buried beneath the Kingsbury conglomerate, which rests on the older beds with obvious angular unconformity.

Other maps showing truncated faults

79. Atoka folio, Okla.
98. Tishomingo folio, Okla.
166. El Paso folio, Tex.
183. Llano-Burnet folio, Tex.
207. Deming folio, N. M.

Truncated Dikes

Maps

24. Three Forks folio, Mont.
68. Walsenburg folio, Colo.
141. Bald Mountain-Dayton folio, Wyo.

Dikes, when they are intruded, will not, presumably, all rise to a single horizon and then stop. If then, several dikes stop at the base of a given formation, the suggestion is very strong that they have been truncated by erosion, and the higher formation laid down on this erosion surface.

On the Bald Mountain quadrangle (Folio 141), for instance, the numerous dikes cutting the pre-Cambrian granite all appear to end abruptly at the contact of the Deadwood (Ꞓd). It is very obvious that these dikes are buried, and that the contact is unconformable. The same relation is shown by the Nussbaum formation in the west central rectangle of the Walsenburg folio (No. 68), where it clearly overlies two dikes. Tilted and buried sills have the same significance. An example occurs near the north end of the fifteen minute meridian on the Three Forks sheet (Folio 24).

Other examples of truncated and buried dikes

120. Silverton folio, Colo.
142. Cloud Peak-Fort McKinney folio, Wyo.

HISTORY INVOLVED IN AN UNCONFORMITY

Maps

24. Three Forks folio, Mont.
142. Cloud Peak-Fort McKinney folio, Wyo.

Two important elements enter into the evaluation of an unconformity, the lost record (missing beds) at any given point, known as the *stratigraphic hiatus*, and the time involved in the erosion responsible for this break, known as the *time value* of the unconformity. On the Three Forks folio (No. 24), near the intersection of the reference line *A-A* with the forty-five minute parallel, the

Bozeman lake beds (Nb) rest across a truncated syncline. At the center of the syncline the Bozeman rests on the Montana beds (Kmc), and the stratigraphic hiatus is late Cretaceous and early Tertiary. On either flank, the Bozeman rests on the Archean gneisses, and the hiatus is nearly the whole geologic column, including late pre-Cambrian, all of Paleozoic and Mesozoic, and early Tertiary. Between these points the Bozeman rests on beds of various age. The stratigraphic hiatus is not only perfectly definite at any given point, but is also determinate at any particular place, although it varies rapidly and irregularly from place to place, depending on the amount of uplift and the intensity of erosion.

Although erosion in the making of this particular unconformity removed some thousands of feet more sediment on each flank of the syncline than in the center, it is to be presumed that all parts of this small area emerged at about the same time, and underwent erosion through about the same interval. The reason that more was cut away from some parts than from others is the greater rapidity of erosion, due largely to higher uplift. The time value, therefore, is very nearly the same for all parts of the syncline, though the hiatus varies enormously.

Presumably, no part of the syncline emerged in the making of this particular unconformity, until late Montana or later, and when it did emerge it all did so approximately at the same time. Then erosion, working more rapidly on the more elevated portions, removed more rock from some parts than others, in approximately equal time units. Finally, the region again became the site of deposition of the Bozeman, again about simultaneously over all the syncline. The time value is the actual time the region was undergoing erosion in the making of this particular unconformity. It does not exceed late Cretaceous and early Tertiary, or, to be more specific, it cannot be greater than from the latter part of Montana time through Laramie and Eocene, into early Neocene. It may be considerably less than this. For instance, if we follow this syncline along its axis a short distance we see that the Laramie is present, folded into the

trough. We may, therefore, say with much assurance that the erosion that brought about this unconformity did not begin until late Laramie time, or later. This reduces our estimate of the time value to even closer limits.

It may be summed up, then, that the stratigraphic hiatus is definite at any given point, determinate at any given point with a fair degree of accuracy, but may vary rapidly and irregularly from place to place, even within a small area. The time value, in contrast, though perfectly definite at any given point, can usually be determined only within fairly broad limits. The larger the area examined, as a rule, the more accurately these limits may be placed. Over restricted regions, also, the time value is approximately the same for all parts of the area. The larger the region studied the less true will this be.

A still more careful study of the preceding map (Folio 24) suggests that this interval is really divided into two episodes of diastrophism, separated by the deposition of the Livingston. The unconformity at the base of the Bozeman affords a fine illustration of the enormous length of geologic time. In an interval not longer than from late Laramie to early Neocene, the great ranges of this area were folded, probably in two episodes, and thousands of feet of beds, involving nearly the whole geologic column, were completely stripped off over large areas.

On the Fort McKinney quadrangle (Folio 142), there is an unconformity between the Bighorn limestone (Ob) and the Madison limestone (Cm). The hiatus is everywhere very nearly the same, because the emergence did not involve any considerable folding, and, consequently, about the same amount of erosion occurred over all parts of the area. The missing beds involve all of the Silurian and Devonian, and possibly late Ordovician and early Mississippian so far as can be seen on the map. The time value cannot be greater than from late Ordovician to early Mississippian, and may be much less if the Silurian and Devonian. or any part of them, were once deposited here.

The angular unconformity at the base of Tbg on the Fort McKinney sheet has a widely varying stratigraphic hiatus, the

maximum involving all the beds between pre-Cambrian and Tertiary, the minimum only those from late Cretaceous (Kds) to Tertiary. Where Tbg rests on the pre-Cambrian granite, the missing history actually involves several successive periods of sedimentation and erosion, all of which merge into one great unconformity which never could be properly evaluated were it not for the sedimentary record preserved in adjacent sections. The time value of the latest of these (between the De Smet and Tbg) is not greater than from late Cretaceous to some time in the Tertiary. The major folding can be divided into at least two episodes, one post-Piney and pre-Kingsburg (see discordance and truncated faults in T. 51 N., R. 83 W.), and the other post-De Smet and pre-Tertiary (T. 50 N., R. 83 W.). Again, this fact emphasizes the great length of geologic time, when one appreciates that the major folding, of which there seem to be two episodes, and the removal of the rocks of nearly the whole geologic column between the pre-Cambrian and Tertiary, all took place within a small portion of late Cretaceous and early Tertiary time.

THE DRAWING OF STRUCTURE SECTIONS

Maps

141. Bald Mountain-Dayton folio, Wyo.

Since width of outcrop is so intimately related to dip and to topography (pp. 230–232), it is well, especially in a deeply dissected region, to construct a topographic profile (p. 17) to scale before attempting to draw a cross-section. Undue exaggeration of the vertical scale should be avoided, inasmuch as such exaggeration distorts the thickness and the dip of beds, and gives an untrue picture of the structure. To emphasize this point, the student should be required to draw a section, using the same vertical as horizontal scale, and then another along the same line, exaggerating the vertical scale five or ten times. A section along *A-A* in the north central rectangle of the Bald

Mountain sheet (Folio 141) is especially suited to bring out the effects of such distortion.

The beginner should also guard against too small a scale, as it is much easier to see complex structure if the lines are not too closely crowded.

After the topographic profile has been constructed on a suitable scale, the next step should be the location on its surface, by dots, of all contacts crossed, care being taken to place the contacts accurately. It is best not to attempt to draw any beds until all contacts are located, and the appropriate map symbols placed over each belt of formation. The positions of all faults should also be located by dots.

The student should then decide whether the faults are high- or low-angle, and if the former whether they are probably normal or reversed. The fault planes should then be drawn with the appropriate slope to indicate the type of fault probably present.

Next the direction and the approximate angle of dip at each contact should be estimated, and short lines drawn downward from the located points in appropriate directions. As yet, these lines should not be continued farther than to indicate their direction of slope. If there are igneous rocks, it is highly important to determine whether they are intrusive or extrusive, and of what type, as batholith, dike, sill, etc., in order correctly to represent their probable relations. The unconformities should also be located. It is customary to represent them by irregular wavy lines.

Finally, the contact lines should be connected up, care being exercised to show each formation with its appropriate thickness, and not to exaggerate unduly the depth of synclines, a common fault with beginners.

Naturally, the only way to learn how to draw structural cross-sections is to draw many such, and excellent results can usually be attained in the laboratory by having a member of the class draw a section on the board, subject to class criticism. Beginning with the simpler structures, greater and greater complexities can be introduced. In such work, topography should be roughly

approximated and width of outcrop estimated. In this way attention is not distracted from interpretation of the structural complexities, by excessive efforts at exact measurements. After the general method of attack is clearly understood, and some proficiency attained in interpreting the more complex structures, drill should follow in the making of numerous more exact drawings.

The use of coordinate paper in plotting profiles is usually helpful, as a time-saving device.

REPRESENTATION OF STRUCTURE BY CONTOURS

There are in use several types of contours that show subsurface conditions. Of these, the commonest is the structural contour (or isobath) map. Another type is the map showing depth lines; and, finally, in some cases, contours are drawn to show old buried topography. These will be discussed briefly in the following paragraphs.

STRUCTURE CONTOUR MAPS

Maps

23. Nomini folio, Md.-Va.
84. Ditney folio, Ind.
102. Indiana folio, Pa.
123. Elders Ridge folio, Pa.
127. Sundance folio, Wyo.-S. D.
136. St. Marys folio, Md.-Va.
160. Accident-Grantsville folio, Md.-Pa.-W. Va.
174. Johnstown folio, Pa.
     Bull. 686, U. S. Geol. Survey.

Structure contours, or isobaths, may be defined as lines drawn on the surface of a given bed through points of equal elevation. Surface in this sense, of course, does not mean erosion surface, but the original contact of one bed with the next bed above or below. Such lines are not even drawn at unconformable contacts, where this can be avoided, inasmuch as irregularity of

contour is introduced that results not from folding, but from inequality of erosion and deposition. These structure contours bear no necessary relation whatever to topographic contours representing the land surface. This may be clearly seen by a study of the Elders Ridge structure sheet (Folio 123), the absence of any relation between the two sets of contours being particularly conspicuous. The structure contours picture the configuration of the folded bed, and are for the most part far below the surface of the ground, though they intersect the topographic contour of the same number at the outcrop of the bed on which they are drawn. On the Elders Ridge sheet (NW. rect.), for instance, the 1,000-foot structure contour intersects the 1,000-foot topographic contour on the outcrop of the Upper Freeport Coal, the bed on which the contours are drawn. The structure contours are above the ground surface where this bed has been removed by erosion, as near the junction of North Branch with Cherry River, where the 1,000-foot structure curve cuts the 920-foot topographic curve.

On some maps, the structure contour is allowed to end at the point where it passes from below the ground surface; in other words, the portion that would be up in the air is omitted. This is the case on the economic sheet of the Accident folio (No. 160), where all contours are drawn on the top of the Pottsville (Cpv) and stop at the contact of that formation with the overlying Allegheny (Ca). This is likely to be the case when the economic resource for which the contours were drawn is not found in the area from which the contours are omitted. On this map, the lines were drawn chiefly to show the lay of coal beds, and, since there is no workable coal in the area below the top of the Pottsville, contours where the Pottsville or older beds outcrop would have no economic value.

Inasmuch as folding produces a much more regular surface than erosion, structure contours are usually much more regular or gently curved than topographic contours. This may also be clearly noted on the Elders Ridge sheet. Such extreme regularity, however, as is shown on the St. Marys folio (No. 136)

probably results in part from generalization caused by insufficient data.

The interval is determined by the scale of the map, by the amount of vertical deformation, and by the amount of information available. With small-scale maps, in highly folded regions, intervals of 50 or 100 feet may be used. In regions of gentle folding, or on larger-scale maps, 5, 10, 20, or 25 feet may be more satisfactory. Anything under 5 feet would appear to be a waste of time, as the inaccuracies of structural mapping are usually that large. In mapping very large structures, such as the entire Black Hills, much greater intervals may be used (Folio 127, Fig. 3).

Structural contour maps may be made either from data secured by a detailed field survey, or from well logs. In either case, the result is a large number of elevations on the surface of a given bed. Points of equal elevation are connected by lines which show the shape of the fold. Since it is difficult either in the field or in drilling to locate most contacts exactly, minor inaccuracies will creep in that make it scarcely worth while to use an interval of less than 5 feet, and rarely to use less than 10 feet.

If elevations are taken on more than one bed, the vertical interval between the beds is determined, and this interval is added to elevations taken on beds below the contoured horizon, or subtracted from elevations on beds above that horizon. The interval is usually variable, and considerable errors are common, owing to inability to determine this variation. Charts, known as isochore charts, are sometimes prepared to show this variation. Such a change in interval is rather strikingly shown on the artesian sheet of the Nomini folio (No. 23). Contours are drawn at the top (solid line) and at the base (long and short dash) of the water-bearing beds of the Pamunkey formation. The interval between the two horizons may be gotten by subtracting the two contours where they cross. Near the west border of the map (cent. rect.) it is 300 feet minus 150 feet, or 150 feet, whereas farther south (SW. rect.) it is 350 feet minus 300 feet, or 50 feet. In other words, this portion of the Pamunkey thins rapidly southeastward.

Although structural contours may sometimes be drawn for purely scientific purposes, such as the delineation of a large uplift like the Black Hills (Sundance folio, No. 127, Fig. 3), they are more often prepared to guide in the search for some economic resource, such as oil or gas (Bull. 686, U. S. Geol. Survey, maps), coal (Accident-Grantsville folio, No. 160), or water (St. Marys folio, No. 136).

The depth to the contoured horizon is easily obtained by subtracting the structural from the topographic contour at the given point. On the structure sheet of the Johnstown folio (No. 174), for example, the northwesternmost structure contour on the map shows the Lower Kittanning coal to be 1,600 feet above sea level. This contour at its northeast end intersects the 2,020-foot topographic contour, which means that the land surface is 2,020 feet above sea level. The depth to the coal bed is, therefore, 2,020 feet minus 1,600 feet, or 420 feet.

On the above sheet, the shape of the folds of the Appalachian Plateau is well displayed. The vertical deformation measured from the crest of the Laurel Ridge anticline to the trough of the Johnstown syncline is not greater than from 900 to 3,050 feet, or 2,150 feet, nor less than from 950 to 3,000 feet, or 2,050 feet. That portion of the Laurel Ridge anticline shown on the map is pitching northeast; the amount of pitch from the 3,000- to the 2,000-foot line being 1,000 feet in 8.4 miles, or about 119 feet per mile, which is but little over a degree. The dip on the steepest part of the southest flank, from the 3,000- to the 1,250-foot line is 1,750 feet in 1.85 miles or about 946 feet to the mile, which is between 10 and 11°. This illustrates the usual tendency for the pitch of a fold to be much less than the dip on its flank.

It should be noted that the axis of the Johnstown syncline is offset by cross-folding, and that there are two distinct "lows" with a saddle between. The local "high" should also be noted on the axis of the Ebensburg anticline. On the economic sheet of the Indiana folio (No. 102), the Chestnut Ridge anticline shows several such local "highs", a very characteristic condition.

The "highs" referred to above are "closed", that is, contours extend about them in closed curves. Richmond anticline (Folio 102), on the other hand, is a typical "nose", or pitching fold without closure, at least on this map.

These folds of the Appalachian Plateau should be contrasted with several from Oklahoma. For this purpose the maps in Bulletin 686, United States Geologic Survey, are particularly useful, especially Plate XX. On this map it may be noted at once that there is a general regional west dip, much modified by local warping. Along the north border of the map the Foraker limestone, the contoured horizon, drops from 1,375 feet in the northeast corner to 1,160 feet in the northwest, a fall of 215 feet in 6 miles, or about 36 feet per mile, which is under a half degree. On the south border, it drops from 1,365 in the southeast corner to 1,175 feet in the southwest, or 210 feet in 6 miles. Thirty-five feet may, therefore, be considered as about an average figure. This dip is regional on the west flank of the Ozark uplift.

Whiteface dome in sec. 35 may be taken as a typical example of the folding in this region. It is mapped with a 5-foot interval, as contrasted with 50 or 100 feet on the maps previously cited. The point at which oil, trapped under this dome, would begin to spill up the regional dip is about at the center of the south line of sec. 36. This is known as the *spilling point.* The difference in elevation between this point and the crest of the dome is called the *closure.* It cannot be less than the difference in elevation between the lowest and the highest closed contours on the dome, 1,355 to 1,375 feet, or 20 feet. The crest of the dome, however, may be almost as high as 1,380 feet, and the spilling point almost as low as 1,350 feet so that the closure might be almost 30 feet. It, obviously, lies somewhere between limits of 20 and 30 feet. The maximum dip of the west flank of the dome is where the contours are most closely crowded, between the 1,365- and 1,285-foot curves. Here the drop is 80 feet in about 0.7 mile, or nearly 115 feet per mile, which is slightly over 1°.

North Bird Creek anticline (sec. 15) has no closure, and would ordinarily be termed a nose. It is really a plunging anticline, pitching southwest.

The Ditney economic geology sheet (Folio 84) represents the regional west dip off the Cincinnati uplift. Along the twenty minute parallel, the drop of the Petersburg coal is from 550 to 250 feet in about 18 miles, or approximately 17 feet to the mile. It is essentially the same at the south border of the map. The contours are much more regular in this area than on the Oklahoma map mentioned in the preceding paragraphs. This may signify less local warping, or it may result from less adequate data in preparing the map, and conclusions should be drawn with some caution.

The sharp curve in the 350-foot structure contour with its apex at Littles (T. 1 S., R. 8 W.) is a syncline pitching slightly south of west. The synclinal nature of this minor warp may be clearly seen by remembering that the area within the loop shows the coal at below 350 feet (between the 300- and 350-foot lines), while immediately to the north and south it is above 350 feet, the loop obviously representing a local downwarp.

The extremely regular contour lines on the St. Marys folio (No. 136) indicate that the coastal plain has undergone comparatively little local warping. Nevertheless, this regularity is doubtless considerably overdone, owing to lack of adequate data and consequent generalization. Here the regional dip from the 400- to the 600- foot lines is 200 feet in about 16¾ miles, or approximately 12 feet to the mile. To avoid confusion, one must remember that these contours are below sea level, so that the dip is southeast, even though the numbers on the contours increase in that direction.

The behavior of structure contours with respect to faults is well shown on Plate XXIV, Bulletin 686, United States Geological Survey. Along the fault in sec. 21, for instance, at one point the 400-foot line abuts against the 410-foot contour, the throw there being about 10 feet, with the southwest side raised. At another point, nearer the center of the fault, the 390-foot line matches against the 420-foot contour, a throw of about 30 feet.

Other maps illustrating the use of structure contours

110. Latrobe folio, Pa.
159. Independence folio, Kan.
175. Birmingham folio, Ala.
185. Murphysboro-Herrin folio, Ill.
186. Apishapa folio, Colo.
188. Tallula-Springfield folio, Ill.
189. Barnesboro-Patton folio, Pa.
195. Belleville-Breese folio, Ill.
200. Galena-Elizabeth folio, Ill.-Iowa.

DEPTH-LINE MAPS

Maps

68. Walsenburg folio, Colo.
85. Oelrichs folio, S. D.-Neb.

Instead of drawing structure contour lines through points of equal elevation of a given bed, lines are sometimes drawn through all points at which the given formation is equally deep below the surface of the ground. These are less graphic to the geologist in picturing structure, but are more easily read by the layman, who does not have to make any subtraction (p. 327) to determine the depth of the formation in question. Such maps are commonly used in showing the ground-water resources of a region.

A moment's thought will make it clear that, with perfectly horizontal formations, depth lines will conform strictly to topography; and that with absolutely plane topography, they will perfectly delineate structure, but that with folded rocks and a much dissected region, the depth to any given bed will be controlled both by the structure of the bed and the topography of the area, so that depth lines will not truly delineate either feature.

The artesian water sheet of the Walsenburg folio (No. 68) affords a very clear illustration of this method of delineating subsurface conditions. The zero depth curve, of course, follows the outcrop of the formation. About the border of Greenhorn

Mountains (NW. rect.), where the beds dip steeply, this curve crosses divides and valleys with but little relation to topography. In this northeast rectangle, on the other hand, where the beds are very nearly horizontal, the zero curve follows the topographic contour much more closely. The effect of faults (SE. rect.) is to offset these curves, since the bed delineated will be deeper on the dropped than on the raised side of the dislocation.

In order to make the map still more easily interpreted by the layman, the areas between successive depth lines may be indicated by distinctive colors or patterns, as on the Oelrichs artesian sheet (Folio 85). Further consideration of depth lines will be deferred to the section on "Hydrologic Maps" (p. 333).

Additional maps showing the use of depth lines

36. Pueblo folio, Colo.
58. Elmoro folio, Colo.
99. Mitchell folio, S. D.
100. Alexandria folio, S. D.
107. Newcastle folio, Wyo.-S. D.
127. Sundance folio, Wyo.-S. D.

CONTOURS ON UNCONFORMITIES

Maps

100. Alexandria folio, S. D.
165. Aberdeen-Redfield folio, S. D.

It is sometimes of importance to know the configuration of an old buried land surface, and contours may be drawn on such a surface, just as on a recently carved topography, provided enough data are available. Where the unconformable contact outcrops, surface data may be utilized, but where it is buried, its position cannot be determined by the thickness of the intervening beds, as is done in locating structural contours, and the subsurface portions of such curves are drawn almost wholly from information secured in mining or drilling operations. Of course, since bore holes are rarely closely spaced, except in prospecting or develop-

ing some economic resource, such as lead, coal, oil, or the like, it rarely happens that sufficiently detailed information is available to make these contours more than the crudest generalizations.

Contours on such a buried erosion surface, though they are in a sense representations of subsurface conditions, are essentially topographic contours, and should show the same wealth of detail, if all the information could be secured. In practice, however, they are usually smooth curves, such as those on the Alexandria folio (No. 100), drawn on the top of the Sioux quartzite. Even on this map,the lines are, obviously, much generalized, but on the Aberdeen quadrangle (Folio 165), where the depth to the Sioux quartzite is much greater, and the number of wells penetrating to it consequently fewer, the generalization is greater, as shown by the increased smoothness of the curves. This smoothness may, of course, be in part a response to a less rugged erosion surface, but is also surely in part a result of lack of data. It is readily apparent that the slope of such surfaces even where correctly determined may not conform to the original land slope, because of later warping.

Civil engineers sometimes draw essentially similar maps of bedrock surfaces beneath deep residual or glacial soils.

Contours drawn on the top of the "Mississippi Lime" in Oklahoma, with a view to showing structure in lower sands such as the "Tyner" or "Wilcox", are certainly open to criticism, in that the contact is notably irregular, and so-called "highs" that are commonly supposed to be structural may be purely topographic, and have no reflection in lower beds.

Other maps showing contours on old erosion surfaces

96. Olivet folio, S. D.
97. Parker folio, S. D.
99. Mitchell folio, S. D.
114. De Smet folio, S. D.

HYDROLOGIC MAPS

Maps

23. Nomini folio, Md.-Va.
36. Pueblo folio, Colo.
68. Walsenburg folio, Colo.
85. Oelrichs folio, S. D.-Neb.
100. Alexandria folio, S. D.
136. St. Marys folio, Md.-Va.
152. Patuxent folio, Md.-D. C.
156. Elk Point folio, S. D.-Neb.-Iowa.
165. Aberdeen-Redfield folio, S. D.
182. Choptank folio, Md.
209. Newell folio, S. D.

Water Supply Paper 423, U. S. Geol. Survey, Pl. II.
Water Supply Paper 495, U. S. Geol. Survey, Pl. IV.

Several types of maps are in use in the study and development of underground waters. The ordinary structure contour map (pp. 324–330) has been employed in certain areas, particularly along the Atlantic coastal plain. The St. Marys folio (No. 136) affords a good example, contoured on the base of the Miocene. At St. Inigoes (SW. rect.), the artesian horizon is 450 feet below sea level, and the land surface 100 feet above, so that a drill would have to penetrate approximately 550 feet of sediments before reaching the base of the Miocene. The artesian horizon dips seaward at the rate of 50 feet in about 4 miles, or approximately 12½ feet per mile. According to the legend, flowing wells can be obtained only at elevations less than 20 feet above sea level.

Contours may be drawn on several water-bearing horizons, as on the Patuxent quadrangle (Folio 152). Here the dip in the Magothy formation of the Cretaceous (green contours) from the +100- to the −400-foot curve is 500 feet in 13.6 miles, or about 37 feet per mile; while that of the Calvert formation of the Eocene (red contours) between the 0- and the 200-foot contours is 200 feet in about 17.7 miles, or about 11 feet to the mile. There is, therefore, a measurable discordance in dip between these beds, probably marking post-Cretaceous and pre-Eocene tilting.

On the Patuxent sheet, the strike is essentially the same for all the formations contoured (a structural contour, of course, being a strike line). On the Nomini sheet (Folio 23), on the contrary, one set of structure contours crosses another at a marked angle. This discrepancy in strike is also well shown on the Choptank folio (No. 182).

These variations of dip, strike, and thickness, naturally, have a very important bearing on the depth of drilling to the lower horizons. Such variations cannot be discovered from surface information alone, but are dependent on the available logs (detailed records) of holes already put down.

Depth lines (pp. 330–331) probably present to the lay mind a somewhat more easily interpreted picture of the availability of a water-bearing horizon, and are much more extensively used than structural contour maps in describing ground-water resources. The Walsenburg quadrangle (Folio 68) affords a typical illustration. In the extreme northeastern part of the map, the depth lines conform very closely to the surface contours, which indicates (p. 330) that the strata are nearly horizontal, and the depth to the Dakota varies chiefly with the topography. In the western portion, on the other hand, where the discrepancy is greatest between the topographic contours and the depth curves, the beds are considerably tilted, and the depth to the Dakota varies, both with the dip and with the topography.

The colors used in the legend of the Walsenburg folio are explained for the most part on the map. The reason the areas of flowing wells (blue) are restricted to the deeper valleys is almost wholly a matter of elevation at the curb. One interesting factor not explained in the legend is the loss of head as the eastern outcrops of the Dakota are approached. This is probably a matter of leakage. On Cuchara River, for instance, the elevation at the curb would be lower in the east central than in the south central rectangle. Still, flowing wells occur at the higher elevation, and not at the lower, presumably because excessive leakage at the outcrop (E. cent. rect.) has reduced the head, until flowing wells are impossible. On the Pueblo sheet (Folio

36), the boundary of the area of flowing wells conforms much more closely to the contours than on the Walsenburg folio. This means that it is controlled more completely by altitude at the curb of the well, and is presumably much farther from any excessive natural outlet that can reduce the head unduly.

The effect of outcrop and natural leakage on head are also well shown on the Elk Point quadrangle (Folio 156), on which the area of flowing wells dies out down river as the outcrop of the Dakota is approached. On the eastern half of the Alexandria sheet (Folio 100) the Dakota water-bearing horizon is absent, cut off by preglacial erosion. The great depth of glacial drift over the region, however, acts as an effective seal, and prevents much loss of head, which loss would probably be total were the drift seal not present.

To make the depth-line artesian map even more graphic for the layman, it is now common practice to color the areas between successive depth lines in distinctive shades or patterns. The Elk Point folio (No. 156) affords a typical illustration of this practice. The line between the 0-100 and the 100-200 green patterns, of course, is the 100-foot depth line for the Dakota sandstone. The very close conformity of these pattern boundaries with the topographic contours indicates the great regularity of the subsurface structure.

In portions of the Great Plains, the eroded surface of the pre-Cambrian Sioux quartzite marks the depth below which it is hopeless to expect a water supply. As data from numerous wells accumulate, it is possible to draw very generalized contours on this unconformity for guidance in predicting the lower limit of profitable drilling. The orange-colored contours on the Alexandria quadrangle (Folio 100) are a much generalized representation of this old rock floor. On the Aberdeen quadrangle (Folio 165), the depth to this horizon is much greater and the wells penetrating it presumably fewer, so that the configuration of the old floor is shown in still more generalized form (see pp. 331–332).

On many water-supply maps, lines are also drawn through points of equal artesian head. On the Newell quadrangle (Folio 209), for instance, the green line marked "2700" is drawn through all points along which the water of the Lakota sandstone will rise in a well and stand at 2,700 feet above sea level. Since on this folio no topography as low as 2,700 feet occurs along this line, no wells drilled along the line will flow. On the 2,800-foot artesian head curve, on the other hand, that part of the area below 2,800 feet will yield flowing wells, whereas that part above 2,800 feet will not.

The intake for this area is the Black Hills, and the head decreases with distance, owing to friction. The variable spacing of the lines of equal head is probably a response to a change in the permeability of the water-bearing sand. The lines of equal head are particularly erratic on the Oelrichs quadrangle (Folio 85).

In areas where porous formations, such as alluvial fan deposits, are more or less uniformly saturated with ground water not under artesian head, contours may be drawn on the top of the water table (Plate IV, Water Supply Paper 495, U. S. Geol. Survey). At any given point, the elevation of the water-table contour subtracted from that of the surface contour will give the approximate depth it is necessary to dig for water. Thus, at Yuba City, T. 15 N., R. 3 E., the indicated depth is about 10 feet, and at Plainfield, T. 9 N., R. 1 E., about 20 feet.

Like structure contours, such data are also readily convertible into depth lines (Plate II, Water Supply Paper 423). Figures in blue placed beside well symbols give the data from which these lines are drawn. This map also differentiates by a color scheme the areas where ground water is being absorbed from those where it is being discharged and dissipated.

Other hydrologic maps

58. Elmoro folio, Colo.
71. Spanish Peaks folio, Colo.
99. Mitchell folio, S. D.
107. Newcastle folio, Wyo.-S. D.

114. De Smet folio, S. D.
117. Casselton-Fargo folio, N. D.-Minn.
135. Nepesta folio, Colo.
137. Dover folio, Del.-Md.-N. J.
168. Jamestown-Tower folio, N. D.
173. Laramie-Sherman folio, Wyo.

MISCELLANEOUS ADAPTATIONS OF CONTOURS

Maps

Water Supply Paper 144, U. S. Geol. Survey, Plate II.
Water Supply Paper 275, U. S. Geol. Survey, Plate XI.

The principle of contours is well suited to the illustration of numerous geological features, where there is a progressive variation of some factor or quantity over a wide area. Thus they may be used to indicate the amount of some salt or radicle in the ground water of a region (Plate XI, Water Supply Paper 275), or the amount of chloride due to wind-blown salt spray along a shore line (Plate II, Water Supply Paper 144). Such lines may be called isochlors.

Similar lines are used to indicate the amount of fixed carbon in coals, over large areas. Conversely, these also denote the amount of volatile hydrocarbons, and for this reason have been called isovols (Jour. Wash. Acad. Sci., vol. 5, no. 6, pp. 189–212, 1915, Fig. 1). Contours have also been used to show the variation in the thickness of delta deposits (Grabau, "Textbook of Geology;" vol. 2, p. 332, 1921). Similar applications may be made for other purposes.

GEOLOGIC HISTORY OF AN AREA

Maps

142. Cloud Peak-Fort McKinney folio, Wyo.

Much of the geologic history of a region may be read from the map and accompanying legend. A single suggestive illustration will be given in the following paragraphs, limiting the interpreta-

tion to facts and deductions which can be made legitimately from this particular map without reference to printed reports, or to maps of adjacent areas. For this sort of interpretation, the Fort McKinney quadrangle (Folio 142) is particularly well fitted, as there is a wide range of interpretative problems to be considered. Reference will be made only to the one sheet of the folio. It will be assumed that the age of all rocks is correctly stated in the legend, since there is no way, from the map alone, to check the age determinations made during the course of the field work.

The first event of which there is definite evidence is the intrusion of a great granite batholith into some pre-existing rock, of which not even the slightest remnant now remains exposed. The granitic texture in an acid rock forms the necessary evidence that it is an intrusive, and, for it to be an intrusive, some earlier rock must have once existed, into which it could have been intruded. After the intrusion, but before middle Cambrian time, the granite underwent fracturing, and into it were intruded diabase dikes. That these are pre-middle Cambrian is evident, since they are abundant in the granite, but nowhere cut the Cambrian or younger beds, while at two points they seem to be buried by the Deadwood formation.

Following this igneous activity came a period of profound erosion, that carved away the rock into which the granite was intruded, and presumably much of the granite itself, truncating the diabase dikes. The next event is the encroachment of the middle Cambrian (Acadian) sea, and the deposition of a series of sediments of mixed character but of unknown sequence that record changes of sedimentation conditions which cannot be worked out without more definite knowledge of the sequence of the conglomerate, sandstone, shale, and limestone members of the Deadwood.

Some time after the close of middle Cambrian (assuming that the Deadwood is correctly placed), but before Bighorn time, the region emerged and underwent erosion. Whether beds later than Deadwood and earlier than Bighorn were ever deposited is

uncertain, but if they were they have been completely removed by erosion. The emergence must have been slight and very even and without local warping, as the Deadwood has nowhere been completely removed.

Since the legend gives no statement as to the part of Ordovician time represented by the Bighorn, it is not possible, from the map alone, to state very accurately either the stratigraphic hiatus or the time value of the unconformity. The region, so far as the map can be read, may have emerged by, or even before, the close of middle Cambrian, and remained out of water until late Ordovician. Or it may not have emerged until after lower Ordovician, for instance, and then have suffered the removal of later Cambrian and lower Ordovician, during middle Ordovician time, with resubmergence in the latter part of the period. The use of the text of the folio, of other maps, and of later published reports, of course, would make it possible to evaluate this break more closely.

Some time in the Ordovician the region was submerged, and the Bighorn limestone laid down in seas that were either far removed from a land mass, or else, if adjacent to a continent, then to one standing so low that but little clastic material was being delivered to the sea.

At or after the close of Bighorn time, which from the available data may be any part of the Ordovician, the region emerged. Silurian and Devonian beds are entirely lacking, and the next horizon is of Missippian age. A wide range of interpretations might be possible, regarding this lost interval. So far as can be seen here, the region may have been land even through late Ordovician, all of Silurian and Devonian, and part of early Mississippian. On the other hand, it is possible that it remained under water throughout all of Ordovician, Silurian, and Devonian time, and suffered all its erosion in the early Mississippian, during which time all beds above the Bighorn were completely removed. The last supposition is hardly probable, inasmuch as it would require a great deal of erosion, at a very uniform rate, and to a uniform depth, so that no remnants of the intervening

beds were left. Still it is a possibility. On the other hand, it is perhaps more than likely that during so long a time there were several oscillations with alternate deposition and erosion, making the lost interval fairly complex. Much information not shown on this map is available as to the general history of this missing interval, but it must be excluded in a purely map-reading exercise. In any event, the uplift must have been without much local warping, since the Madison everywhere rests on the thin Bighorn limestone, which was nowhere completely removed during the interval.

Some time in the Mississippian, the region was again submerged, and land masses were either so remote, or so low, that little clastic sediment was contributed to the sea during Madison time. Shale and sandstone layers in the Amsden suggest rejuvenation of contributing continental areas, which probably increased, with or without emergence, so that only sand was being delivered to the sea of this area in Tensleep time. Following this, but without any definitely recorded break, there seems to have been actual emergence, though the land of this area was still low enough to be the site of deposition, in the form of "Red Beds", which, because of their high degree of oxidation, and presence of gypsum, are commonly interpreted at least in part as of terrestrial origin, under conditions of aridity.

Although no unconformities are noted from the beginning of Madison to the close of Chugwater time, it seems highly improbable that any area of epicontinental sea remained submerged or even low enough to receive continuous sedimentation throughout so long a time. At or after the close of Chugwater deposition, sufficient uplift seems to have occurred to bring about erosion on the site of the former terrestrial deposits, and some time in the Jurassic, though whether early, middle, or late is not shown, the region was again submerged, the green shales and associated limestone quite probably being indicative of marine conditions.

Following the Sundance marine episode, there is a succession of shales and sandstones in which the absence of limestone and the rapid alternations of material are clearly indicative of an

active land mass at no great distance. It is entirely possible that this series may vary between marine and terrestrial.

At or after the close of Piney deposition came uplift with pronounced folding and faulting, followed by deep erosion. Inasmuch as the preceding sedimentary beds covered wide areas and must have been deposited in an essentially horizontal position, it follows that uplift was much greater along the western border of the map than elsewhere, and folding and faulting also, presumably, more intensive. The next formation, the Kingsbury conglomerate, buries truncated faults, and rests with marked discordance on beds as old as Madison (T. 51 N., R. 83 W.). Its composition and position indicate derivation from the underlying formations and it must, therefore, have been derived from the relatively higher area to the west.

This episode of profound deformation and erosion, occupying but a small part of a single geological period, affords a very convincing argument in favor of the enormous length of geologic time.

The Kingsbury might, so far as the evidence goes, be either marine or terrestrial, but the De Smet which follows it clearly represents deposition on a low-lying swampy land surface, under humid conditions, as evidenced by the beds of coal. Following De Smet time, there seems to have been a mild renewal of deformation, since these beds are tilted as high as 12 to 15° over considerable areas, dips hardly to be interpreted as initial. Following this tilting was further erosion, and the deposition of the Tertiary (?) bench gravels discordantly across all the older rocks. The form and the position of these patches of bench gravel make it almost certain that since their deposition there has been uplift, and consequent dissection of the gravel deposits.

Following this, came one or more episodes of glaciation, and at present the whole area is being actively eroded.

APPENDIX TO PART II

NUMERICAL LIST OF FOLIOS AND REPORTS USED IN PART II

(The letter "s" after a page number indicates supplementary list, without discussion.)

INDEX

NOTE: Complete lists of maps used in this work, fully indexed, will be found in Appendix I, pp. 206–213, and Appendix II, pp. 342–344.

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